Energy for Building – Improving Energy Efficiency in Construction and in the Production of Building Materials in Developing Countries

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Foreword

Over the past decade there has been a rapid increase in both awareness and concern about the impact of buildings on the global environment. There is concern at one level about the health of the living environment within and around buildings, and there is concern also about the impact of the resource use in buildings on the global environment. There is a growing commitment in some of the industrialized countries to reduce the use in buildings of products whose deterioration will damage the global environment, of hardwoods which are contributing to the loss of the tropical forests, and of energy from non−renewable sources, and the pollution consequences of the use of fossil fuels. These problems are all directly related to energy use or have energy implications, since whatever solutions are found will have some bearing on energy.

In many countries the proportion of the total national energy consumption used in buildings is over 50 per cent and this figure tends to be higher for developing countries. While the largest part of this energy relates to the energy consumption of the building in use, the energy used in the production of buildings is a significant and a growing element of this total energy use.

Of equal concern to the United Nations Centre for Human Settlements (Habitat) is the problem of meeting the need for adequate shelter, especially for the poor in developing countries, as expressed in the Global Strategy for Shelter to the Year 2000. Successive reports by the Centre have detailed the inadequacy of the living standards in those countries. In addition, inadequate housing is a serious problem for a growing proportion of the population in many industrialized countries also.

Increasing the efficiency of energy use in building−materials production is important for three further reasons, apart from the obvious advantage of energy saving: it can help to make durable building materials available at prices which the average poor households can afford; it will help to reduce the environmental degradation caused by the excessive use of biomass fuels, and conserve them for household use; and it will help to reduce the need for imported building materials or production processes. It is, therefore, hoped that this publication will prove useful to building−materials producers, designers, builders and policy−makers in the field of housing and construction, especially in developing countries.

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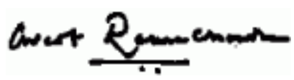

Dr. Arcot Ramachandran
Under−Secretary General
Executive Director

I. Introduction

1.1 Buildings, energy and the environment

The link between the use of energy in buildings and the total energy use is well established. The link between energy production and use and local and global environment is causing increasing concern worldwide. There are thus good environmental reasons for seeking to reduce the energy "embodied" in buildings. In the developed countries there is a growing demand for an environmental impact assessment of all building projects which will include consideration of embodied energy,[1] although this is not yet commonplace.

1/ Royal Institute of British Architects, *Buildings and Health: the Rosehaugh Guide* (London, 1991).

Equally, there is the problem of meeting the need for adequate shelter for the people of the developing countries. Various reports[2] have detailed the inadequacy of the living standards which are being experienced by many millions in those countries. The scarcity and cost of durable building materials is regularly identified as one of the main obstacles to better housing standards. As populations grow and become more urbanized, the soil and vegetable materials on which traditional rural building methods have depended are no longer cheaply or freely available, and they are being replaced by processed or factory−made materials. Many of the well−established technologies for small−scale processing have been inherited from a time when energy, in the form of biomass, was more abundant than it is today or will be in the future, and they are highly energy−intensive. As a result the materials they produce are too expensive for the poor. Likewise the large−scale processing technologies imported from the industrialized countries are energy−intensive and tend to rely on high−grade energy imports.

2/ United Nations Centre for Human Settlements (Habitat), *Global Report on Human Settlements, 1986* (New York, Oxford University Press, 1987).

This publication examines the question of energy efficiency in building materials from the point of view of producers of building materials, building designers and builders. Producers will want to know how they can change their production processes so as to reduce energy consumption (and cost), how energy consumption can be reduced by changing the raw materials, the product mix or specification used, and how energy costs can be reduced by changing to different energy sources. They will also want to know how to go about conducting an energy audit of their operations.

Designers and builders will want to know how the choice of building materials affect the total embodied energy content of a building; how much energy is used in construction and how this can be minimized; how substitutions between materials might be made to save energy without sacrificing performance in other respects; and how building−materials selection affects the lifetime energy consumption of a building, including manufacture, construction, use and maintenance, and demolition. They will want to know how to make estimates of energy consumption for proposed buildings.

All three groups will want to know what techniques are available for application now, and what techniques are currently under development or might become available in the near future. The document is also intended to be of use to policy−makers in the field of housing and construction who will be interested in the conclusions of the report about the most effective actions to be taken by each group.

Chapter II examines the energy use in the production of a range of separate materials which together comprise more than 90 per cent of materials used in building. It looks at the broad characteristics of building−materials production processes. It then examines in greater detail the processes available for producing metals, cements, ceramic materials, and mineral and vegetable materials, identifying the opportunities for improved energy efficiency through the choice of processing technology and plant management. It identifies techniques which are already well−established, and points to some promising developments. Chapter II also looks at the effect of both scale of production and transport costs on total energy consumption in building materials to the point of use, and considers how the optimum strategy for plant location could be developed. It concludes by looking at the possible contribution of recycling to reducing the energy cost of building materials.

Chapter III moves to the energy content of building components. Those who select materials and components for use in a building project −whether as designers or as builders − have the greatest control over the amount of embodied energy used. But they need to know how the energy content of different alternative components or elements of the building compares, rather than the individual materials of which the element is made. This is the sum of the embodied energy in all the materials used plus the energy used in the construction process. The chapter looks in particular at a range of alternatives for binders, for walling materials, and for roofing materials, and attempts to make comparisons between technologies giving comparable performance. It also looks at the energy content of complete building systems, and considers the particular case of insulating materials where increased energy costs in manufacture can be offset by improved energy efficiency in the lifetime use of the building. The opportunities for energy saving for designers by making use of recycled materials (or buildings) is also discussed.

Chapter IV sets out a range of strategies for producers, builders and designers to optimize energy use. For each group it also suggests some strategies for policy−makers, administrators and legislators in the construction industry in developing countries.

1.2 The pollution consequences of energy use in building materials

Pollution arising from the production of building materials arises at three levels. At the local level (under 1 km), pollution is caused by gases produced in the combustion of fuels, causing health risks to workers and local residents. At the regional level (up to 100 km) pollution can cause climatic modification through thermal effects or persistence of particles in the atmosphere. These local and regional effects can normally be controlled by reducing the emission of the substances responsible, and many governments have pollution control or environmental protection regulations setting required standards.

Some of the pollutants emitted in building materials production processes also contribute to pollution on a continental or global scale. Sulphur dioxide resulting from coal−burning, for example, can result in acid rain causing acidification of lakes and destruction of forests. But potentially the most important effect is the phenomenon of global warming caused by increasing concentration of the so−called greenhouse gases in the atmosphere. The gases primarily responsible for this and their approximate contribution are shown in table 1.1. As will be seen, the greatest contribution is made by carbon dioxide emission which is a virtually unavoidable consequence of all combustion processes.

The potential consequences of global warming are so serious at so many levels of human activity that international protocols on reduction of carbon dioxide emissions are certain to be formulated in the near future.[3] These will have implications for all processes involving combustion, and in particular for building materials production processes. The contribution of any process to global warming, unless any other of the gases listed in table 1.1 is emitted, is in direct proportion to the total carbon dioxide produced. This in turn relates to the amount of primary energy used. However, the type of fuel used can affect the greenhouse gas emissions very significantly. Table 1.2 shows some typical values of the carbon dioxide emissions which result from the supply of one gigajoule (GJ) of energy to a process, using different fuels. The important points to note are that electricity produces 2.5 times as much carbon dioxide as coal, while natural gas produces only 60 per cent as much. Fuelwood produces about 10 per cent less carbon dioxide than coal, a similar amount to petroleum.

3/ International Conference on Climate Change.

In any particular region these figures might be slightly different, especially the figure for electricity use which depends on the mix of fuels used to generate electricity in any region. Where a substantial part of this is from either nuclear, hydroelectric or other renewable sources, use of electricity contributes less to carbon dioxide emissions. However, the complex of risks and low−level pollutants associated with nuclear power then becomes a significant issue.

Table 1.1. Contributions to greenhouse warming by various gases

Gas	Contribution to warming (percentage)
Carbon dioxide	50
Methane	19
CFCs	17
Tropospheric ozone	8
Nitrous oxide	4

Source: Henderson and Shorrock (1990).

Table 1.2. Carbon dioxide emissions from various fuels[a]

Fuel	CO_2 emissions, kg/GJ	
	Primary energy	Delivered energy
Coal	91	92
Natural gas	50	55
Oil (petroleum)	69	84
Electricity		231

Source: Henderson and Shorrock (1990).
a/ Figures for delivered energy include overheads of generation and distribution.

The principal measure which can be taken to reduce the energy pollution associated with building−materials processes is to reduce their total primary energy consumption. The many means to achieve this are described in chapter II. Similarly, chapter III discusses how to reduce the embodied energy consumption in a building. In addition to these measures, some reduction in greenhouse gas emissions can also be achieved by fuel substitution in processes. The possible benefits of fuel substitutions in terms of carbon dioxide emissions are shown in table 1.3. Where use can be made of renewable energy sources instead of fossil fuels there is a direct benefit in the reduction of greenhouse gas emissions.

The extent to which biomass fuels can be considered as contributing to atmospheric carbon dioxide accumulation depends on how far the trees or other plants cut are being allowed to regenerate. Where forests or plantations are being managed for continuous energy production, the net production of carbon dioxide will be much less than that produced by one−off cutting for fuel since carbon dioxide is absorbed from the atmosphere by growing trees. Since many small−scale building−materials production processes can make use of biomass fuels, this could provide an additional incentive for using them rather than large factories which use significant amounts of fossil fuels. But it is assumed in this report that reducing the consumption of biomass fuels is just as important as reducing the consumption of other types of fuel.

1.3 Life−cycle energy costing

The idea of life cycle costing of a building is that when design decisions are made, consideration should be given to the total cost associated with each design alternative, over the entire lifetime of the building, including:

- Capital cost of construction
- Annual running and maintenance costs
- Costs of subsequent major refurbishments
- Cost of eventual demolition and waste disposal

Frequently, clients are concerned primarily or exclusively with capital costs, which can be accurately estimated, and they fail to make allowance for the future costs which are more difficult to predict and are often borne by the tenants or users of the building. This has led to the design of buildings which are cheap to build, but have large annual running costs. It has been repeatedly shown that relatively small increases in initial costs, for instance in improved insulation, can pay for themselves in a relatively short period through reduced running costs.

Now that energy conservation has become an important issue in building design, it is logical to apply the same principle to the energy costing of a building project, and to look for ways to minimize the total energy consumed during the building's lifetime including the contribution from each of the phases referred to. Because the bulk of the energy used in most buildings during their lifetime comes from the annual energy consumption, most attention understandably tends to be given to ways of reducing this component of the total energy, and it is easy to ignore the other components.

Replace fuel on left by fuel on right: reduction in carbon dioxide emission shown in kg/GJ

Replace \ by	Solar	Natural gas	Methanol from wood	Oil	Fuelwood	Coal	Oil from coal	Methanol from coal	Gas from coal
Lignite	150	101	94-87	80	72	62	41-31	27	(-)3-31
Gas from coal	119-147	70-98	56-91	49-77	41-69	32-60	0-39	(-)4-25	
Methanol from coal	123	74	60-67	53	45	35	4-14		
Oil from coal	109-119	60-70	47	39-49	31-41	21-32			
Coal	88	39	25-32	18	10				
Fuelwood	78	29	22-16	8					
Oil	70	21	7-14						
Methanol from wood	56-63	7-14							
Natural gas	49								

Table 1.3. Reductions in CO_2 emission by fuel substitution

Based on Kellogg and Schwarz (1984): data from a number of United States and European sources.

Yet, even though the total quantity of energy consumed in a building during its lifetime may be many times that consumed in its construction, there are a number of reasons why the energy−use in the construction process, and in particular in the building materials used, should be treated as a matter of importance in looking for ways to minimize energy−use in the built environment as a whole.

Although smaller than household energy use, energy consumed in building−materials production is by no means insignificant in national and global energy budgets: the materials industries, of which building materials comprise a large proportion, are, in general, energy−intensive, and have been shown to account for over 20 per cent of world fuel consumption.[4]

4/ Chapman, 1975.

Many building materials are manufactured in processes involving high−temperature kiln technologies and crushing and grinding operations which are inherently energy−intensive, but in which there is a wide difference in energy consumption between the least and the most efficient technologies available, offering scope for substantial energy savings through the use of more energy efficient technologies.

Within the range of technologies available for producing any particular material, there is often scope for replacing high−grade energy, such **as** electricity and liquid fuels, with relatively low−grade energy, such as solid fuels, agricultural waste and other unconventional fuels. There is also scope for increasing use of solar energy in some processes.

There are very large differences between the inputs of purchased energy needed for the manufacture of different materials, and there is thus substantial scope for substitution of lower−energy materials for higher−energy materials in building design without compromising on other aspects of performance.

In most cases, the energy embodied in the materials of which a house is made will be several times larger than the annual consumption of energy in use, so there will be a faster return on savings made in construction energy than on equivalent savings made in recurrent energy consumption.[5]

5/ Connaugton, 1990.

Building designers have much more direct control over the total amount of energy embodied in a building, through the selection of materials, than they have over the amount of energy consumed annually in use, which is greatly affected by the way the occupants use the building.

All these considerations apply as much to buildings in industrialized as in developing countries, but the question of embodied energy has a special urgency in many of the poorer developing countries which are in a process of rapid urbanization. The change from rural to urban settlements is often accompanied by a rapid change from the use of almost zero−energy renewable building materials such as earth, stone and thatch to higher−energy factory−made permanent materials such as brick and concrete. New factories for the production of these materials are now being established in large numbers in the developing countries, with the result that national energy consumption in the building−materials sector (particularly of high−grade fuels) is rising rapidly. As a part of the same process building materials manufacture is increasingly concentrated in fewer, larger−scale production plants, to take advantage of economies of scale, thus increasing the transport component of the energy cost.

There are alternative materials which could be used which make use of local raw materials, use relatively little processing energy, and could be manufactured locally with low resulting transport costs. Estimating the real energy costs of such processes is one of the topics covered in the next chapter.

II. Optimizing energy use in building−materials production

2.1 Energy analysis

The purpose of energy analysis is to evaluate the total quantity of energy which has to be taken from primary energy resources in order to produce a given commodity or service.[6] To be complete, the analysis has to include not only the direct use of fuels in the production process, but also the amount of fuel used in obtaining the raw materials used in the production process, and in transporting them to the factory. It should also include the energy used to make and maintain the machinery used in the production process. The total quantity of energy calculated in this way is called the gross energy requirement of the commodity, and is expressed in the appropriate energy units.

6/ Chapman and Roberts, 1983.

Figure 2.1 illustrates the process of energy analysis, and shows that four levels of energy use can be distinguished. The first is the energy used in the process itself. The second is the energy used in the production of the materials used in the process. The third combines the energy used in the equipment and other inputs to the production process. The fourth includes the machinery needed to make the machines and the material inputs. It has been found[7] that levels 3 and 4 are unlikely to contribute more than 10 per cent at most to the gross energy requirement, so they can generally be ignored, in obtaining a first approximation. In many building−materials manufacturing processes, where high−temperature kiln operations are involved, the primary energy use in level 1 alone gives an adequate approximation to the ex−factory energy content, since it is much larger than all other contributions. This is true for cement, bricks, lime and glass production. But transport energy to bring these materials to site may nevertheless be significant.

7/ Ibid., p. 100.

Figure 2.2 illustrates the range of inputs which may need to be considered in estimating the gross energy requirement of a fairly simple building, the embodied energy. The range of building materials used is very wide, and the source of each material which is usually not known at the time of specifying the building can have a significant influence on the total embodied energy.

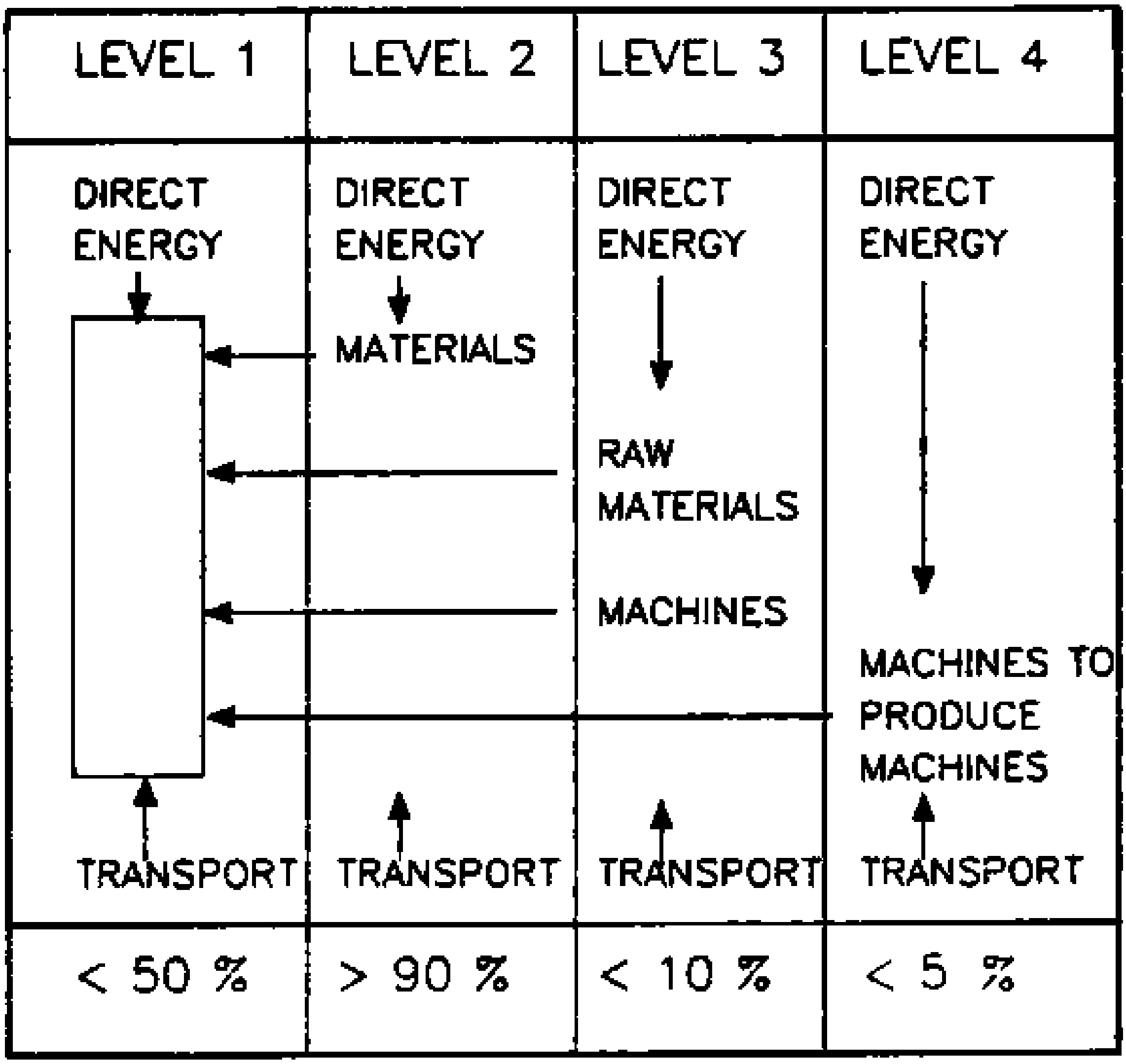

Figure 2.1. Materials and energy flows in building production

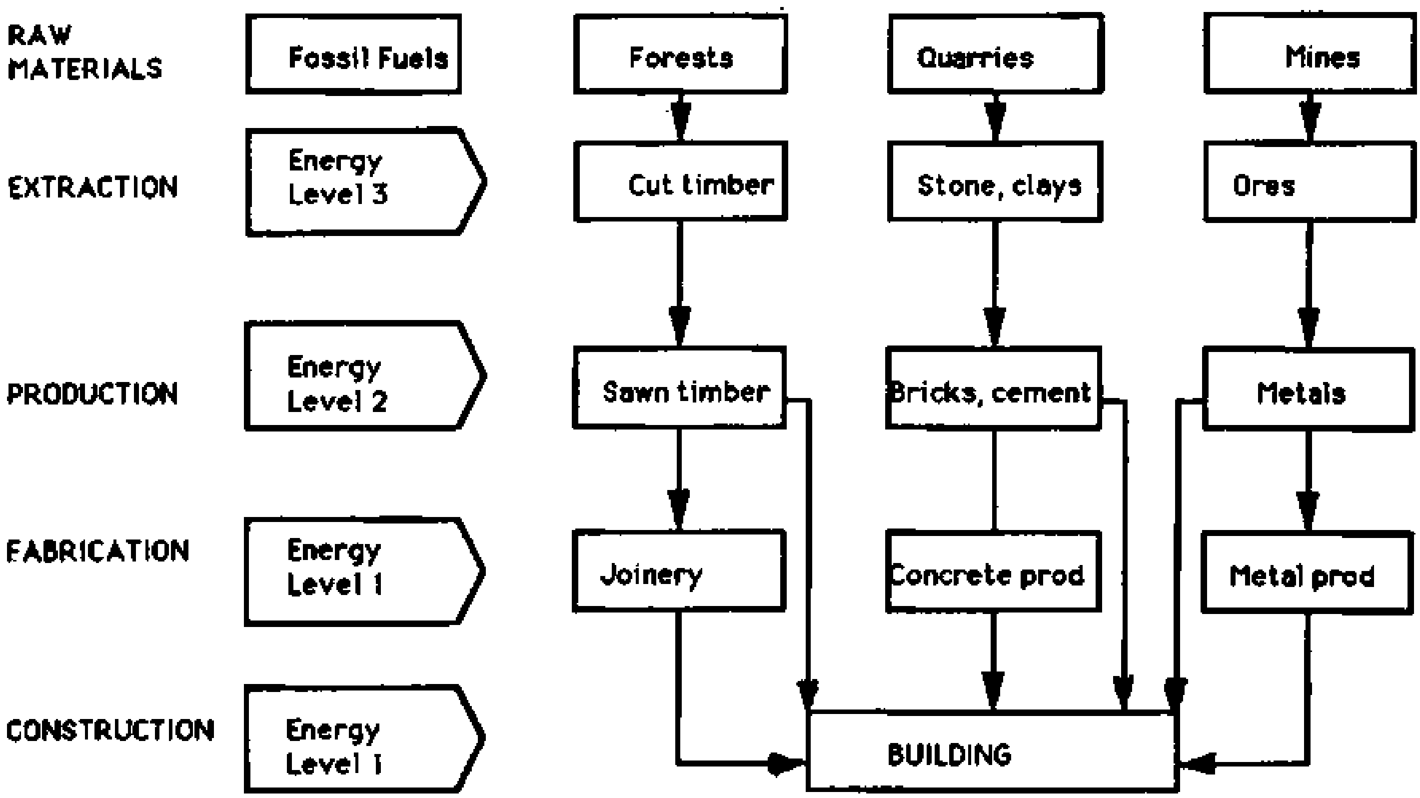

Figure 2.2. The sources of the energy used in building production

However, a high proportion of the energy used in most buildings is used in the production of a small number of key materials, including concrete, mortar and plaster, bricks and blocks, and timber. Data on the energy requirements of the most important building materials are presented in this chapter. Some data on these materials are available from a variety of sources and these have been converted into a consistent set of units for comparison. The figures for any material may vary over quite a wide range. Some reasons for these variations include:

- Different assumptions about the inclusion of indirect−energy costs
- Differences between the production processes considered
- Transport costs resulting from international trade
- Assumptions made about the extent of recycling
- Whether fabrication costs have been included.

There is also a tendency for best−practice figures to be given, which may mean that some of the figures given represent better than average performance.

For the materials manufactured in large−scale processes, most of the data available are for industrialized countries. Some adjustments may be needed for developing countries depending on the extent of local manufacture or import. For materials manufactured in small−scale processes, data are available from a range of sources, including developing countries, but are often based only on the process energy requirement rather than the gross energy requirement. Thus care is needed in the interpretation of the data presented in the following sections.

2.2 Energy intensity in building materials manufacture

There are numerous studies estimating the energy costs in the manufacture of various materials,[8] although many of them derive from the 1970s when work on energy conservation began to betaken seriously. Since in most cases these are a mixture of electrical and thermal energy costs, the most suitable basis of comparison is in terms of primary energy, which includes energy used in the energy conversion and supply system. The use of energy in quarrying operations and the transporting of raw materials to the factory also needs to be included. The range of different estimates given in these studies is the result in part of the different assumptions made, but is also a reflection of the wide range of different technologies in use for any one material; this point will be discussed further below.

8/ For example Haseltine, 1975, Stein, 1977, 1981, 1981, Chapman 1975, Chapman and Roberts, 1983, Spence and Cook, 1984, Lawson, 1990.

On the basis of the energy intensity, (the gross energy requirement to manufacture unit weight), building materials have been classified[9] into three categories: high, medium and low−energy materials. High−energy materials are those with energy intensities greater than 5 GJ/ton. Medium−energy materials are those with energy requirements between about 0.5 and 5 GJ/ton. Low−energy materials are those with energy requirements less than 0.5 GJ/ton. Other ways of defining high, medium and low are sometimes used,[10] and it may be valuable to define a class of very−high−energy materials with energy intensities above 50 GJ/ton. The classification of the major materials used in building worldwide is shown in table 2.1.

9/ By Spence and Cook, 1984.

10/ For instance, by Lawson, 1991

High−energy materials

The high−energy materials are those with energy intensities greater than about 5 GJ/ton of the manufactured material and include aluminium, steel, plastics, glass and cement. All these materials are manufactured by processes characterized by large scales of production, and incorporating high−temperature operations. Much of the energy consumed is the thermal energy of the fuels used. There has been rapid development in the technologies of production of these materials in recent years, leading to reduced energy consumption, and generally to larger average production units. For instance, there was a 33 per cent improvement in energy intensity (energy used per unit value added) in the British steel industry between 1953 and 1980, as older less efficient plant was replaced by newer more efficient manufacturing plant.[11] In many developing countries where older plant remains in use, the energy costs of these materials can therefore be expected to be significantly higher than in industrialized countries. But reductions in energy consumption may also be possible through different manufacturing processes, without necessarily increasing the scale of production. The case of cement, the most important of the high−energy materials produced primarily for use in the building industry, is discussed below.

11/ Chapman 1976, Bending and Eden, 1984.

Table 2.1. Comparative energy requirements of building materials

Material	Primary energy requirement (GJ/ton)
Very−high−energy	
Aluminium	200−250
Plastics	50−100
Copper	100+
Stainless steel	100+
High−energy	
Steel	30−60
Lead, zinc	25+
Glass	12−25
Cement	5−8
Plasterboard	8−10
Medium−energy	
Lime	3−5
Clay bricks and tiles	2−7
Gypsum plaster	1−4
Concrete:	
In situ	0.8−1.5
Blocks	0.8−3.5
Precast	1.5−8
Sand−lime bricks	0.8−1.2
Timber	0.1−5
Low−energy	
Sand, aggregate	<0.5
Flyash, RHA, volcanic ash	<0.5
Soil	<0.5

Medium−energy materials

The medium−energy group of materials are those with energy requirements between about 0.5 and 5 GJ/ton of the manufactured material. This group includes concrete, lime, plaster and most types of building blocks based on cement or lime, and fired−day bricks and tiles. Scales of production tend to be much smaller than for the first group, and they often use traditional technologies, some of which are of poor efficiency. There has been substantial research into improved methods of manufacture of these materials in recent years, but because of the scattered nature of the industry, the rate of dissemination and application of this research has been slow. The opportunities for energy savings are substantial, as indicated by the case of clay brick manufacture, discussed below.

Low−energy materials

The low−energy group of materials comprises those requiring energy inputs less than about 0.5 GJ/ton. The group includes aggregates for concrete and mortars, natural and artificial pozzolanas, soil and stabilized soil.

Timber is generally in this category if locally grown, although where, as in many parts of the industrialized world, it is an imported commodity, the energy in transport and treatment generally brings it into the medium−energy category. Apart from timber, a general characteristic of this group of materials is that they are not normally used in building on their own, but as a part of a composite, in association with a higher−energy material. In many cases, the traditional methods of producing these materials make extensive use of human or animal labour, which is increasingly being replaced by mechanical energy. The value of trade−offs between manual energy and mechanical energy is considered below in connection with the case of soil construction.

In addition to the differences in the quantity of energy used, there are also significant differences in the quality of energy or fuel used. The high−energy materials commonly depend on high−grade fuels such as electricity, oil and pulverized coal in their manufacturing processes − for many countries these energy sources are particularly scarce and associated with import costs. By contrast, the medium−energy materials, particularly bricks, tiles and lime, can often use lower grade fuels such as firewood, low−grade coal or oil, sawdust and crop−waste, which may be more available. They can also often utilize solar energy for drying processes. Most of the low−energy materials use little purchased energy, though they may use significant amounts of human or animal labour.

A final difference which is characteristic of the three types of manufacture is that the high−energy materials tend to be manufactured in larger production units, and therefore require more energy in distribution to the point of use than for the medium or low−energy materials. The energy cost of transporting building materials 100 km by road is about 250 MJ/ton.[12] Thus the transport energy of delivery of bricks from a large−scale brickworks or block plant where the average delivery radius might exceed 100 km would add 10 to 15 per cent to the total energy cost of the delivered materials; for a large scale cement works in a developing country even larger delivery distances are common. Transport by rail or water are considerably cheaper in energy costs, however: figures of 50−100 MJ/ton for rail and 70−100 MJ/ton for water for each 100 km transport distance have been given.[13] Transport costs are further discussed in section 2.10.

12/ Bending and Eden, 1984.

13/ Ibid.

2.3 Energy consumption in the production of cementitious binders

Portland cement

Cement is very widely used throughout the building industry. Cement manufacture is an energy−intensive industry; the cost of energy constitutes approximately 25 per cent of the price of finished cement. Worldwide, some 600 million tons of cement are produced annually, using about 4.2×10^9 GJ of primary energy or about 1 per cent of the total world primary energy consumption. Thus the potential impact of energy savings in cement production is considerable.

About 85 per cent of the gross energy requirement of cement manufacture is in the kiln, where temperatures of about 1450°C are reached. But significant amounts of energy, mainly electrical, are also used in raw materials preparation, in grinding and in powering conveying plant.

A number of kiln processes are in use, with widely differing typical fuel consumptions. Most cement plants worldwide use a rotary kiln (see figure 2.3). This is a long cylinder, its axis slightly inclined to the horizontal, which slowly rotates as the raw materials pass down it: combustion gases from the furnace at the lower end of the kiln pass over the raw material, causing them to sinter into cement clinker. The clinker is then cooled and ground in a ball−mill to a fine powder at which stage a small proportion of gypsum is added to the mixture. Older cement plants use a wet process, in which the raw materials, limestone and clay are mixed into a slurry: this provides for easy control over the mixture, but uses a lot of energy in removing the water from the mix during calcining. Thus the wet process has been superseded in most new plants by dry−process plants in which the raw materials are mixed dry. Further improvements in energy efficiency have been achieved by the use of preheaters and precalciners, which improve the heat exchange between combustion gases and raw materials.

In China and India, a number of small−scale plants are in operation, using a vertical−shaft kiln process. In terms of kiln energy efficiency these tend to be better than wet−process plants, but less efficient than the best dry−process plants. The amount of electrical energy used depends on the extent of mechanization of the process, but tends to be slightly lower than large−scale plants. The advantage of such plants is principally that they reduce the distribution costs associated with cement produced in large plants: thus the energy analysis needs to consider the overall energy costs including transport. This is considered in section 2.10.

Table 2.2 shows some representative figures for the energy requirements of the different kiln processes, and typical values for power consumption in the form of electrical energy. These are process−energy requirements rather than gross energy requirements, but as pointed out earlier, they are a reasonable approximation to gross energy requirements and they indicate the relative energy requirements of the different processes.

A number of studies have been made of the potential for energy saving in the cement industry. As will be seen, the principal opportunities for energy saving are in the kiln itself. But there are other possible means of energy saving in cement production apart from the kiln. The principal opportunities for energy saving in cement production are as follows:[14]

- Improvements in kiln energy efficiency, particularly through wet−to dry−process conversions, but also through the adoption of suspension preheaters in dry−process plants

- Utilization of waste heat for materials drying and other industrial processes

- Improved kiln insulation

- The production of blended cements, in which a proportion of the Portland cement is replaced by an industrial waste material, such as pulverized fuel ash (pfa) or ground blast−furnace slag; it is estimated that such cements could replace up to two thirds of all Portland cement production

- Improvements to grinding techniques

14/ United Kingdom Department of Energy, 1981.

Table 2.2. Process energy requirements in various processes of cement manufacture

Process		Process energy requirement (MJ/ton)	Source of data
Dry process (kiln energy)			
Suspension preheater		3300	NATO (Europe)
		3300	ETSU (United Kingdom)
		3600−4000	Rai (India)
Semi dry		5074	Ming−yu (China)
Wet process (kiln energy)			
		5400	NATO
		6100	ETSU
		5700−6500	Rai
Vertical−shaft (kiln energy)			
Europe		3150	NATO (Europe)
India (mini−cement)		4180−4600	Sinha
China		4850	(ave) Ming−yu
Electrical energy			
India		370−440	Rai
China		345−370	Ming−yu
Europe	(wet plants)	334	ETSU
	(dry plants)	424	ETSU

Similar opportunities for energy saving are likely to be found in each country's cement industry, especially those where a high proportion of the cement is produced in older plants. Many countries now produce a growing proportion of blended cements. In India, for example, over 60 per cent of all cement produced is

Portland pozzolana cement, in which up to 25 per cent of pfa pozzolana is added at the final grinding stage. In addition to blast furnace slag, a number of pozzolanic materials can be considered, including ash from burning rice husk and other agricultural wastes, and pulverized burnt clay.

Fuel conversion from costly to cheap fuels can be beneficial in energy terms even if it slightly increases primary energy requirements, because it can reduce costs and save premium fuels. For example an oil−fired plant in Uruguay was converted from oil to a mixture of coal and rice hulls, increasing fuel consumption by 8 per cent, but reducing costs and the use of scarce fuels substantially.[15]

15/ Fogg, M.H. and Nadkarni, K.L., 1983.

The sum of all these energy saving opportunities could amount to as much as 50 per cent of all energy currently used in the cement industry. Nevertheless, all would have capital cost implications and are likely to be implemented only in a situation of rising demand.

There are further technological developments under study at the laboratory level which would enable cements of comparable quality to Portland cement to be produced with lower kiln temperatures. These include the use of fluxes and the development of new materials known as modified Portland cements.[16]

16/ Rai, 1986

A further alternative would be the replacement altogether of Portland cement in many low−strength applications by alternative cementitious materials based on lime or gypsum with an inherently lower energy content. It has been estimated that at least one−half of all Portland cement used in developing countries is used in applications for which a material of much lower strength would be adequate, if not more satisfactory.[17] The energy consumption of these technologies is considered in the following sections.

17/ Spence, 1980.

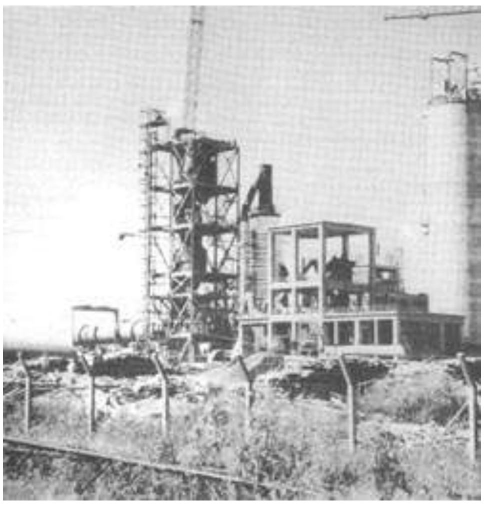

Figure 2.3. Cement kiln under construction. Large−scale cement plants typically have an economic minimum output of 2000 tons per day. In a country with a low consumption of cement, large amounts of energy are used both in production and transport (Mbeya, United Republic of Tanzania).

Lime

Lime is an important building material, with a wide range of uses. Although its principal use in building is as an ingredient in mortars and plasters, it has alternative building uses, in lime washes, sand−lime blocks, and soil stabilization as well as uses in many other industries. Its importance in developing countries is that it can be produced at a small scale using relatively simple technology. Techniques for small−scale production and uses have been described in several publications.[18]

18/ UNIDO, 1985: Wingate, 1985; Spiropoulos, 1984.

In developing countries, many of the potential uses of lime have increasingly been taken over by other materials, notably Portland cement. This is partly because traditional kilns are inefficient and produce a poor−quality lime. Some modern factories producing lime have been installed; and there has also been extensive development work on improved small-scale kiln designs, notably in India,[19] Indonesia[20] and Malawi[21] (see figures 2.4, and 2.5).

19/ KVIC, 1973.

20/ Ceramic Research Institute, 1983.

21/ Spiropoulos, 1991.

A high proportion of the total energy requirement in lime production is used in the calcining process in the lime kiln. This is particularly true of small-scale lime production in developing countries, where material preparation is often done manually. The energy requirement in the kiln can be compared with the theoretical heat requirement. For the purpose of comparing energy requirements, four types of kiln can be distinguished.

- Traditional intermittent kilns; these use either coal or, more commonly, firewood as fuel. The typical output is 1-3 tons per day. They are still quite widely used in the rural areas of some countries.

- Improved small-scale vertical shaft kilns; these are designed for continuous production, and may use either firewood or coal, or other fuels, but other handling operations are manual. The scale of output typically up to 10 tons per day.

- Medium-scale mechanized vertical-shaft kilns: generally larger in scale of production, 20 to 100 tons per day, using coal or oil.

- Rotary kilns: these are associated with fully mechanized plants with scales of output in excess of 100 tons per day.

Figure 2.4. Lime can be economically manufactured at a much smaller scale than cement, appropriate to the needs of a predominantly rural population. Shaft kilns can have a high energy efficiency (lime kiln in Indonesia).

Figure 2.5. The output of lime at an even smaller scale of 1 to 3.5 tons per day is possible. Small masonry shaft kilns are cheap to build and can utilize locally available firewood for fuel, but are still much more energy−efficient than intermittent rural kilns (Arusha region, United Republic of Tanzania).

Table 2.3 shows some data on the energy consumption required for the production of quicklime, which is the form in which lime is produced from the kiln. For some uses, lime is sold in this form; for other uses, it is subsequently hydrated, by the addition of water. This is a low−energy process, but the weight is increased by 30 per cent. Thus, the energy intensity of hydrated lime is lower than that of quicklime.

As can be seen in table 2.3, traditional intermittent kilns can be very wasteful of fuel with only 25 per cent efficiency or less. Well−designed small shaft kilns can have a much improved efficiency, even without a large scale of operation, with efficiencies approaching 50 per cent. Among the larger scale, more capital−intensive processes, mechanized shaft kilns can have a greater fuel efficiency, but at a considerably increased capital cost. Rotary kilns are both capital−intensive and wasteful of fuel.

These examples show that the principal means of improving energy efficiency in lime production is improving kiln efficiency. Vertical−shaft kilns should be used, but the precise level of technology that is appropriate will depend on fuel, intended uses, the scale of output required and other factors. Increased fuel efficiency requires increased capital cost, and the benefits need to be assessed against the costs involved.

Gypsum plaster

Gypsum plaster is principally used in the building industry for walling plasters and in the manufacture of plasterboard, although it has a potentially wider range of applications.[22] Because kiln temperatures no higher than 150 × C are needed for calcination, energy requirements are generally much lower than for cement or lime production.

22/ Coburn, Dudley and Spence, 1989.

As in the case of lime, a high proportion of the total energy requirement for gypsum plaster production is kiln energy. The raw material, gypsum, is calcined either by direct heating − mixing it with the fuel and burning the two together−or by cooking it, i.e. by heating it indirectly within a container. The type of kiln used depends on the capital available and the scale of output. Kiln types may be classified as:

- Direct heating: pit kilns:
  shaft and walled kilns

- Indirect heating: flat−plate kilns:
  open−pan kilns
  enclosed kilns
  kettles
  rotary kilns
  pressure kilns/autoclaves.

Direct−heating methods tend to produce a poor quality gypsum plaster with much unburnt or overburnt material. Indirect heating offers better control, and is possible at quite small scales of operation, using flat−plate or open−pan kilns, though quality control and energy efficiency are better with larger, more capital−intensive processes. Most production processes are intermittent or batch processes, though rotary kilns can be operated continuously.

Table 2.3. Energy requirements of quicklime production from various sources

Process and scale	Scale of production (tons/day)	Energy requirement (GJ/ton)	Efficiency (percentage)	Source of data
Traditional intermittent				
kiln, India	Very small	12.6	25	Rai
Conventional shaft kiln,				
India	10−20	9.03	35	Rai
Improved shaft kiln, India	10−20	6.24	51	Rai
Improved shaft kiln, Malawi	3	6.92	46	Spiropoulos
Mechanized vertical kiln,				
India	20−100	4.76	67	Rai
Rotary kiln	<100	6.71	48	Rai
National studies:				
Argentina		3.8		
Germany		8.8		
India		6.34		

Comprehensive data on the energy consumption of gypsum plaster production at all scales are not available. Some examples of the energy consumption using different kiln types and scales of production are given in table 2.4. Even though the smaller scales of production appear to be less efficient in terms of energy conversion, they make use of cheap unconventional fuels while the larger scales of production depend on high−grade fuels.

Even the least efficient processes use substantially less energy than either cement or lime production. However, a direct comparison between the three materials is not possible, because they all have slightly different properties. Comparison on the basis of equivalent performance is considered in chapter III.

2.4. Energy consumption in the manufacture of metals

A variety of metals are used in building. Steel is used structurally, for roof sheeting and in the form of reinforcing bars for reinforced concrete work. It is also used in smaller quantities for nails and screws and other iron−mongery, and for door and window frames. Aluminium is used for roofing sheets, window frames and cladding systems. Zinc and lead are used for roof covering, zinc for galvanizing, copper for electric cables and so on. Although all metals are high−energy materials, the total quantity used in most ordinary buildings is comparatively small, and they do not constitute a high proportion of the embodied energy in the building as a whole. Typically steel represents no more than about 1 per cent and copper about 5 per cent of the embodied energy.[23]

23/ Howard, 1991.

Table 2.4. Comparative energy requirements for gypsum production

Process	Energy requirement (GJ/ton)	Source of data
Large−scale production, UK	0.8 to 1.0	Coburn and others
Calcined gypsum, India	1.5	Rai
Plaster of Paris, Germany	1.5	Rai

Small−scale production, North Africa	2.7 to 4.6	Coburn and others

Most developing countries do not manufacture the primary metal, though they are more likely to have fabrication plants making the actual building products used, such as electric cable, roof sheet etc. Thus energy conservation in the metal−refining industries is of less importance in developing countries

Table 2.5 gives some figures for the energy requirements in the manufacture of different primary metals made in different locations. The energy content in these estimates is derived from all stages of the processing. In looking at the data in table 2.5, the following points should be noted.

(a) These are figures for the production of the primary metal, and do not include subsequent transportation or fabrication processes;

(b) Technical progress in reducing the energy requirements of the metal industries has been fairly rapid, and energy consumption figures are not constant with time (see section 2.2);

(c) As indicated in the figures given for aluminium, production from recycled material uses far less energy than primary production. Thus the energy requirement for all metals is strongly influenced by the extent of recycled material which is used. This explains some of the differences between different figures quoted. This can also be expected to increase over time;

(d) In the case of aluminium, much of the energy use is in the form of electrical energy. The primary energy equivalent depends on whether this electricity is generated by burning fossil fuel or from hydro−electric sources.

The principal ways in which energy can be saved in metal production are.[24]

- Improvements in mining methods and process technology
- Recycling and design for longer life (see section 2.11)
- Elimination of waste in processing and fabrication
- Minimizing the use of metals in end−uses

24/ Chapman and Roberts.

Table 2.5. Comparative primary energy requirements of various metals and metal products

Metal	Primary energy requirement (GJ/ton)	Source of data
Steel:		
Profiled steel, Germany	25.8	Rai
Reinforcing rod, Germany	30.1	Rai
Finished steel, UK	35.9	Chapman
Reinforcing rod, UK	39.5	Chapman
Reinforcing rod, United States	36.4	Stein
Galvanized sheet steel, United		
States	64.5	Stein
Aluminium:		
Sheet, Germany	261	Rai
Finished products, UK	270	Chapman
Plate and sheet, United States	270	Stein
Other metals:		
Copper, UK	115	Chapman
Lead	30	Chapman
Zinc	70	Chapman

The actual embodied energy costs of the metal products used in building depend also on the energy utilized in fabrication, and on any waste generated. Table 2.5 also gives some figures for the embodied energy in fabricated metal products. In most cases these are not very much higher than the embodied energy in the metal from which they are fabricated, but it should be noted that galvanized steel sheet, a very commonly used building product, uses substantially more energy than structural steel sections.

2.5 Energy consumption in brick and tile manufacture

Burnt−clay bricks and tiles are building materials of great importance in developing countries because they can be produced from local materials using relatively simple technologies and whatever fuels are locally available.

The basic raw material is clay, although sometimes admixtures are used. All technologies involve the following stages:

- Winning the raw materials
- Clay preparation
- Moulding
- Drying
- Firing

A great variety of technologies are used for each of these stages ranging from simple manual technologies which have been unchanged for centuries to highly sophisticated mechanized operations. In most developing countries relatively small−scale labour−intensive methods are mostly used, and it has been found that the introduction of mechanized methods, even though they may be more energy−efficient and produce bricks and tiles of higher quality, are not successful because the high capital costs lead to higher prices for the bricks than those produced by traditional producers. Thus emphasis is now being placed on ways to upgrade the techniques used by the small−scale traditional producers.

The bulk of the energy used in all production processes is the kiln fuel required to fire the bricks. This can represent more than 95 per cent of the energy requirement of the entire process in cases where ambient energy is used for drying. In other cases, significant amounts of energy may be needed for drying, for mixing, moulding and handling, but these will rarely exceed 10 per cent of the total process−energy requirement.

Kiln energy

The principal variables affecting the energy requirements of brick kilns are:

- Whether the firing is continuous or intermittent
- The size and heat transfer efficiency of the kiln
- Whether the brick−earth used contains combustible material.

Table 2.6 shows some typical energy consumption estimates for brick kilns, taken from a variety of sources. It is important to note that clamp processes for brick firing use two or more times as much fuel as continuous kilns, such as the trench or Hoffman kiln; this is because they are fired intermittently, and all the energy used to heat the bricks and the combustion gases is lost, whereas in continuous processes the heat in the bricks is transferred to the incoming air, and the heat in the combustion gases preheats the next batch of bricks for firing.

Replacement of intermittent kilns by continuous kilns is not always possible, however, for a variety of reasons:

- Demand may not be large enough to justify continuous production

- The capital cost of continuous kilns is higher

- The amount of land needed may not be available

- The technology for clamp burning is simpler, particularly when only biomass fuels are available

Thus it is important to look for ways to improve the fuel efficiency of intermittent kilns. The main objectives should be:

• To obtain even temperatures throughout the kiln
• To reduce heat losses through the sides and top surface of the kiln
• To recover heat from the combustion gases

This can be achieved by a variety of improvements to the traditional open clamp design, including insulated permanent walls and roofing, improved fuel feed etc. Improved intermittent kiln designs have been demonstrated in Ghana[25] and China.[26] An improved design for a small clamp has been demonstrated in Indonesia.[27]

25/ Parry, 1979.

26/ UNCHS, 1991.

27/ Hill, 1988.

Where continuous kilns can be used, the evidence suggests that beyond a daily output of 10,000 bricks, economies of scale are small, and that low−capital−cost kilns such as the Indian Bull's trench kiln (see figure 2.6) can have a fuel efficiency comparable with the more expensive covered Hoffman kilns used in European countries.

Table 2.6. Energy requirements for manufacture of bricks and tiles from various sources

Process	Energy per unit weight (GJ/ton)	Energy per brick (MJ/ton)	Type of kiln	Type of fuel	Source
Argentina					
Hollow bricks and tiles:					
new plant	2.14		Tunnel		Rai
old plant	4.75				
Solid bricks	4.24		Clamp		
Germany					
Solid bricks	2.61		Various	Various	Rai
India					
Commons (mechanized plant)		4292		Coal	Rai
Floor tiles		8400	Clamp	Cinder biomass	Rai
Floor tiles		4452	Down−	Coal	
Bricks		3696	draught Bull's trench		Rai
Bricks		2940	CBRI High draft		
Bricks		3990	Hoffman		
United Kingdom					
Flettons	1.2	2500	Annular	Coal	ETSU
Commons	1.8 ave	9100	Misc	Coal, oil	ETSU
Facings/engineering	3.9 ave				

A study of the brick industry in Delhi[28] showed that detailed differences in the design of the trench kiln contributed to significant variations in the energy efficiency. The greatest potential for energy saving was by increasing chimney heights, adopting a fixed rather than the traditional moving chimney design, and careful control of the levelling of the kiln floor. Aspects of process control such as sealing the kiln, adequate drying of the bricks, and uniform feeding of the fuel also contributed to energy saving. Overall, the bricks produced by the process had a average fuel consumption of 1.8 MJ/kg of bricks produced, but with individual kiln's fuel consumption varying from 100 to over 300 kg of coal per 1000 bricks, i.e., 2600 to 7800 MJ/1000 bricks.

28/ Gandhi, 1986.

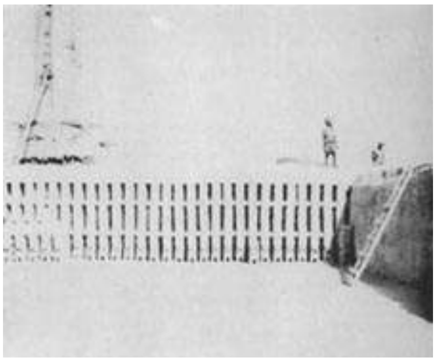

Figure 2.6 Continuous kilns for brickmaking. They are cheap to build and can have an energy efficiency comparable with much larger and more capital−intensive kilns (Bull's trench kiln in North India).

Research on the kiln process at the Indian Central Building Research Institute has led to the development of an improved high−draught kiln design, which is reported to reduce energy consumption by a further 25 per cent compared with a typical trench kiln.[29] But the capital cost of such a kiln is ten times that of the traditional kiln, and consequently it is considered unlikely to be widely adopted at current energy prices.[30]

29/ Rai, 1986.

30/ Gandhi, 1986.

Scarcity and rising prices of coal, the predominant fuel used for brick firing is forcing brick producers everywhere to look for cheaper fuel substitutes as well as energy economies. The same study of the Delhi industry[31] showed that increasing numbers of producers were using a proportion of unconventional fuels, fuelwood, rice husk, sawdust and agricultural waste, and that these producers were able to reduce costs without detriment to the quality of the bricks, though at the cost of a rather small lowering of energy efficiency (see figure 2.7). A small number of producers had eliminated coal entirely, with a resulting increase in energy consumption of only 14 per cent compared with producers using coal alone. Rice husk and other agricultural wastes have long been used as fuels for the firing of rural clamp kilns. In Viet Nam, small rural clamps are fired with fuel bricks which are made from a mixture of coal ash and lake mud.[32] Use of waste engine oil to fire a small kiln in the United Republic of Tanzania has been reported.[33] A possible difficulty in promoting more widespread use of these alternative fuels is that this may cause their prices to rise, and the extent and continuity of their supply might be uncertain.

31/ Lawson, 1991.

32/ Dich, 1987.

33/ UNCHS, 1991

Another way to reduce the conventional energy consumption of kilns is to add carbonaceous wastes (agricultural or industrial wastes containing some combustible material) to the clay mixture. Fly ash and rice−husk ash are both suitable if they have a significant amount of unburnt carbon. Fly ash in India has been found to have typically 6 per cent of unburnt carbon; rice−husk ash has a calorific value of 2 to 2.5 MJ/kg. The effect of these additions is to alter the characteristics of the clay and to affect the properties of the bricks. They can also improve the workability of the clay allowing otherwise unsuitable soils to be used.[34] The resulting bricks are lighter than normal clay bricks, and the resulting savings in fuel could be as high as 35 per cent. Some special clays, such as the Oxford clay in the United Kingdom, contain significant amounts of carbon naturally. This accounts for the very low fuel consumption of Fletton bricks in the United Kingdom (see table 2.6). Unfortunately such clays are not common.

34/ Rai, p. 45.

The fuel consumption per brick can also be reduced by reducing the mass of each unit by increasing its perforations. For each 10 per cent of perforations, the energy requirement is reduced by 5−6 per cent.[35] Small proportions of perforations can generally be incorporated into extrusion processes. Highly perforated bricks, with up to 50 per cent perforations, are common in industrialized countries, but depend on careful selection and preparation of the soil and a mechanized extrusion process.

35/ UNCHS, 1991.

In addition to the kiln energy, the energy needed for drying the bricks and tiles can be significant. In tropical climates, it is often possible to use solar energy for drying (see figure 2.8), but this will usually be possible for only part of the year. Where solar drying is not possible, the drying energy can be obtained by heat recovery from the waste combustion gases in the kiln.[36]

36/ Parry, 1979.

The energy−saving opportunities in brick and tile manufacture may be summarized as follows.

• Where possible, replace intermittent kilns with continuous kilns

• Where continuous processes are used, replace low, movable chimneys with higher permanent chimneys

• If intermittent processes are used, use Scotch or updraught kilns with permanent sidewalls rather than open clamps; improve insulation of clamp kilns

• Add carbonaceous wastes to the clay bodies to reduce the requirement for conventional fuels

• Replace high−grade fuels, such as coal, with lower grade alternatives such as sawdust, agricultural waste and waste oil

• Look for ways to make use of waste heat from combustion in drying

• Use of simple manual equipment for clay processing and moving bricks within the plant (see figure 2.9) rather than mechanical equipment

• Increase the extent of perforations

Figure 2.7. Rice husk is frequently available as a waste material in rice−growing areas, but can be used as a fuel for firing bricks, as shown here in Indonesia.

It has been estimated that heat recovery and the addition of carbonaceous wastes could save 50 per cent of all conventional fuels used in the brick industry in the United Kingdom. In India, potential savings from some of these actions could result in the savings shown in table 2.7.

Figure 2.8. Energy consumption in brick and tile manufacture can be reduced by making use of solar energy for drying the units before they are loaded into the kiln (Yogjakarta Province, Indonesia).

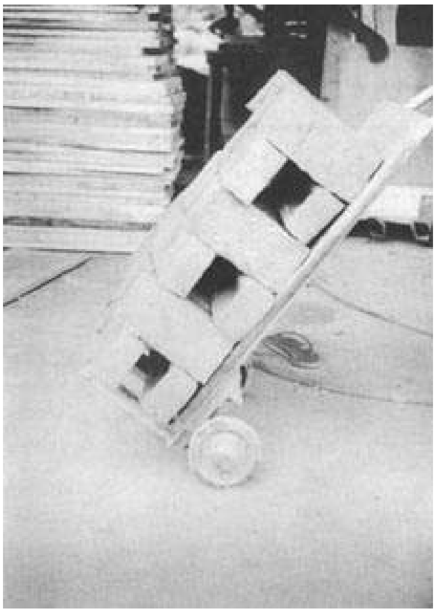

Figure 2.9. The use of well−designed manual equipment for conveying bricks and other building materials during production can save considerable amounts of mechanical conveying equipment and reduce the need for electricity (Ghana).

Table 2.7. Energy savings possible through changes in brickmaking technology in India

Process description	Coal saving (percentage)
High−draught kiln	15−20
Addition of fly ash (30 per cent) to clay	10−30
Addition of coal washery rejects (50−60 per cent)	25−75
Use of rice husk in firing bricks	20−25

Source: Rai

2.6 Energy consumption in the production of mineral materials − aggregates, stone and earth

Sand aggregates and building stone

Considerable quantities of sand and aggregates are used In building everywhere as ingredients in concrete, mortars and plasters. Stone is widely used in the form of dimension stone or rubble stone for masonry work where suitable rock formations are found. These are all low energy materials. The energy used is principally for mining and crushing. In the case of dimension stone some energy for cutting is often required. Depending on the type of economy the methods used range from entirely manual (see figure 2.10) to entirely mechanized. Some values for the energy requirements from different sources are given in table 2.8. These are exclusive of transporting to the building site, and do not include the energy of manual labour involved. This is discussed below.

Earth blocks

Earth blocks are usually made manually (see figures 2.11 and 2.12), and blocks which are unstabilized have a negligible content of conventional energy. When machine compaction is used, the compaction energy required is still very low, less than 0.1 MJ/ton. In this case the energy cost of the block press used should be included, bringing total energy consumption to 50–100 MJ/ton. But unstabilized blocks are of much poorer quality than fired clay bricks or concrete blocks, so this is not a comparable figure. With suitable soils, blocks stabilized with 5 per cent cement have a strength and durability comparable with clay bricks or concrete blocks. An addition of 5 per cent cement would bring the energy requirement of soil blocks to 250 – 400 MJ/ton, still substantially less than the figure for alternative walling materials. Table 2.8 gives some comparable data for earth blocks manufactured in Argentina and Kenya.

In considering materials made by labour intensive methods, it is important to consider in the analysis the human labour involved. Estimating the energy cost of human labour is difficult. One suggested approach[37] is to consider a worker as a 10 per cent efficient machine who consumes about 15 MJ/day, giving an energy output of 1.5 MJ/day. Another approach is to look at the actual energy input to the processes carried out. For instance it has been calculated that the energy of compaction in one soil block compacted in the CINVA–ram machine is about 0.25 KJ;[38] assuming that an equivalent amount of energy is used in ejecting the block, and that 300 blocks per day are produced from the machine, the total energy output is about 150 KJ or about 10 per cent of the above. Another similar approach estimates an average rate of work of about 25 KJ per minute. Sustained work for 5 hours per day would result in a daily energy output of 7.5 MJ. These estimates vary by a factor of 50, indicating the difficulty of putting a sensible figure to human labour.

37/ Rai, 1986.

38/ Spence, 1988.

But let it be assumed that the highest of these figures was adopted, and applied to earth blockmaking technology. Four workers normally produce 300 blocks per day each weighing about 7 kg. The energy input from manual labour would therefore be 30 MJ per day to produce 2.1 tons of blocks, an energy consumption of 14 MJ/ton. This is still only 4 per cent of the energy embodied in the cement used to stabilize the block. It is clear that the addition of the human labour involved would make little difference to the energy costs of most of the processes discussed above, in spite of the fact that it may contribute a very high proportion of the production cost. This reveals a danger that using the energy costs of materials to compare them for use in a building may lead to an overreliance on human labour.

Since in the case of soil blocks the stabilizer is responsible for almost all of this energy requirement, the use of an increased degree of mechanization will have little effect on the overall energy requirement. This is an important conclusion, because one of the principal factors limiting the extent of application of soil–block construction, even in developing countries with very low wage rates, is the very high labour cost involved in typical manufacturing processes, making the cost of production of soil blocks as high or higher than the cost of alternative materials. The key to increased utilization of soil in construction is the development of small–scale industrialized processes to reduce the labour cost. Such processes exist, and where they have been implemented, as in Brazil, the blocks are competitively priced and widely used. Thus soil construction is a case where the strategy for energy minimization in the building industry as a whole may require an increase in the energy costs for one material in order to reduce its production cost.

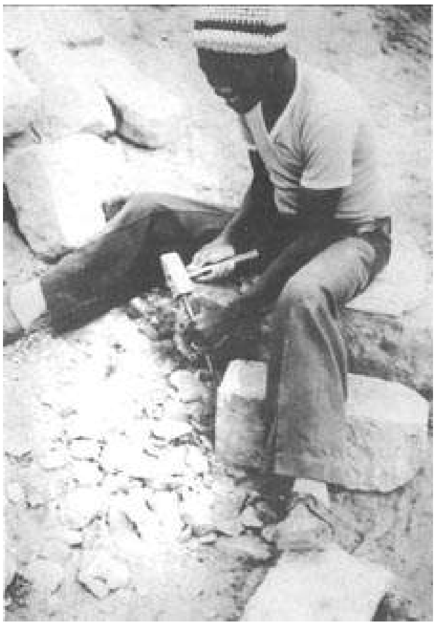

Figure 2.10. Where it is available, stone is a very low−energy building material, which often needs only quarrying and shaping, as here near Nairobi in Kenya.

The low energy costs of the materials in this class also indicate that transport energy should be considered. Assuming a figure of 2.8 MJ/ton/km, transporting 50 km by truck will add 0.14 GJ/ton to the energy requirements of each of the processes in table 2.8, which in most cases more than doubles their extraction and processing costs.

Table 2.8. Energy requirements of mineral materials and earthen blocks in various locations

Material	Energy requirement (GJ/ton)	Source of data
Sand and aggregates:		
Sand aggregate, UK	0.03−0.3	Gartner and Rankin
Crushed aggregate, India	0.22	Rai
Building sand, India	0.015	Rai
Broken stone, India	0.1	Rai
Building stone:		
Building stone, Kenya	0.1	Spence
Earth blocks:		
Adobe blocks, Argentina	0.002	Rai
Asphalt−stabilized adobe, Argentina	0.7	Rai
Cement−stabilized blocks, Kenya 5 per cent cement	0.35	Spence
Cement−stabilized blocks, Argentina 15 per cent cement	0.70	Rai

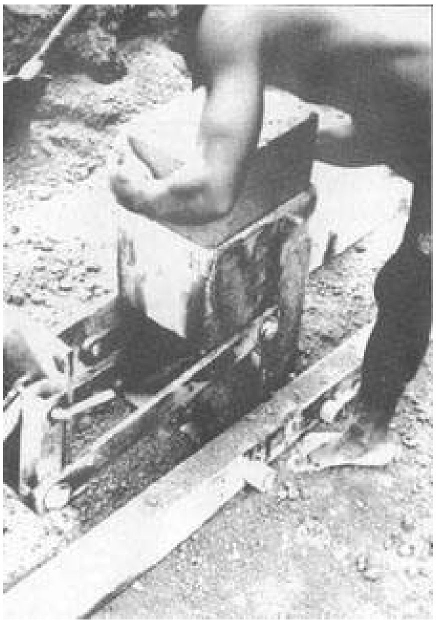

Figure 2.11. Stabilized−soil blocks can be made in a manually−operated press. Stabilized with 5 per cent cement they have an energy requirement for lower than burnt clay bricks or concrete blocks (Kumasi, Ghana).

Figure 2.12. Stabilized soil blocks can also be made using manual compaction. The energy requirement is lower, because less equipment is needed (Lusaka, Zambia).

Thus, in summary, the energy costs of the materials in this class are very low by comparison with materials produced by kiln or factory processing. The main way of limiting the energy consumption is to reduce the transport distance, i.e. to use materials from close to the site. Substitution of mechanical for human energy makes little difference to the total energy requirement.

2.7 Energy consumption in the manufacture of glass

The case of glass is different from the other mineral materials, since its manufacture involves high−temperature kiln processes, and its energy requirement therefore puts it in the high energy category. Glass is widely used in building but, except in special projects, the total quantity used in any building is small. For a typical house it contributes less than 1 per cent to the energy requirement.

Some figures for the gross energy requirement of sheet−glass manufacture are given in table 2.9. Over 80 per cent of this energy is used for melting the raw materials, sand, limestone and soda ash, in furnaces where temperatures of 1450 to 1550 × C are reached. The industry tends to be based on a small number of large producers, and developing countries are substantial importers from the industrialized countries. Energy consumption in the industry in developing countries has been steadily falling. As in the metal industries, the addition of scrap glass (cullet) to the melt is one way of reducing the energy consumption (0.2 per cent for each 1 per cent increase in the cullet ratio), and glass recycling has been steadily increasing in the industrialized countries. There are other opportunities for energy reduction, for instance through better insulation of the process, through improved plant design and recovery and reuse of the waste heat from the process. These would involve additional investment in the industry, and could produce significant returns, but would make little difference to the energy requirement of buildings as a whole.

Where the energy consumption of glass becomes significant is when the lifetime energy consumption of different glazing systems are being compared. The additional savings in energy resulting from the use of double or triple glazing then need to be compared with the energy cost in their manufacture. These tradeoffs are considered in chapter III.

2.8 Energy consumption in the production of concrete and concrete products

Concrete and concrete products are examples of materials which are made by combining the building materials produced in other industries. They may be made either on site as part of the construction process (e.g., *in–situ* concrete), in small–scale production units (see figure 2.13) or in large scale factories. In all cases, the raw materials are cement, sand and aggregates and water. Sometimes steel reinforcement is also used when prefabricated components are manufactured.

Table 2.9. Primary energy requirements for sheet–glass manufacture in different locations

Material	Energy requirement (GJ/ton)	Source of data
Sheet glass, India	21.8	Rai
Sheet glass, UK	11.9	ETSU
Sheet glass, United States	21.4	Stein

Table 2.10. Energy requirements for *in–situ* concrete (after Gartner and Rankin)

Material	Weight (tons)	Energy content (MJ/ton)	Energy (MJ)
Cement (1 m^3)	1.5	7300	10900
Sand–aggregate (9 m^3)	13.5	30–300	405–4050
Concrete (7 m^3)	15		11305–14950
Concrete (1 m^3)			1600–2100
Concrete (0.47 m^3)	1.0		750–1000
Transport energy (1 m^3)			<10
Mixing energy (1 m^3)			<20
Formwork (1 m^3) (and other on–site operations)			<20
Total energy of *in–situ* concrete (1 m^3)			1650–2150

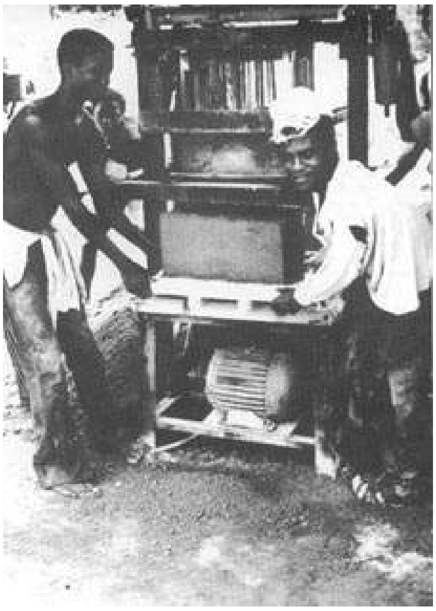

Figure 2.13. Concrete blocks can be manufactured at a small scale. The energy used in the process is primarily electrical energy for vibration. This is a very small proportion of the energy embodied in the cement used.

Table 2.10 shows the way in which the energy requirement for an *in−situ* concrete mix using dense aggregates is estimated. Most of the energy required is the energy embodied in the cement used in the mix.

Transport and on−site energy, which includes the energy content of the formwork used for casting the concrete are comparatively small components.

Concrete blocks and light−weight aggregate blocks used in the construction industry are made from a variety of light−weight aggregates, some of which are by−products of other industries or derived from these byproducts. Sintered pfa and sintered colliery spoil aggregates are made by sintering (burning) the waste product using the residual fuel in the waste, and are thus very−low−energy aggregates. Foamed blast furnace slag and furnace clinker are also used without processing other than grading and are thus also low−energy materials. Other types of light−weight aggregates, such as bloated and sintered clays and shales, use some energy in their processing. Some figures for the energy content of these lightweight aggregates are shown in table 2.11. In some areas volcanic trass may be available as a pozzolanic aggregate. In such cases some cement can be saved, or the blocks can be made with a mixture of trass and lime (see figure 2.14)

The energy content of the blocks themselves per unit weight depends on the ratio of the raw materials themselves and the processing energy. But the energy content which is of most importance for comparative purposes is not that per unit weight, but the cost per unit volume of walling. Many blocks are hollow to improve their insulation value and this also needs to be taken into consideration. Comparative figures for different types of blocks on this basis are shown in table 2.12. Transport costs in reaching the building site have to be added to these figures, but these are comparatively low.

2.9 Energy consumption in the production of vegetable material − timber, bamboo and thatch

Timber and bamboo

Wherever it is available, timber is extensively used as a building material for roof and floor beams and trusses, boarding, framing and panelling. It is also used for door and window framing and for doors and furniture. It is used both in the form of sawn timber and in the form of board − blockboard, particle board and plywood. The principal operations involved in the processing of sawn timber for use in building are felling and transport to the sawmills, sawing, seasoning and preservation treatment. The sawn timber then needs to be transported to the site, and this may involve it being moved internationally by ship and rail or truck. Bamboo has a similar range of uses, but is usually used locally and the international trade in bamboo is less.

Table 2.11. Energy requirements for dense and light−weight concrete aggregates

Aggregate type		Energy requirement (MJ/ton)	Source of data
Dense aggregate		30–300	Gartner
Light–weight aggregates:			
	Sintered clay and shale	3000	Rai
	Sintered pfa	1000	Rai
	Sintered colliery spoil	600	Rai
	Blast–furnace slag and clinker	100	Rai
	Expanded clay	3400	Gartner
	Pfa	18	
	Foamed slag	40	
	Broken stone	99	

Table 2.12. Comparative energy requirements of concrete blocks in various locations

Block description	Location	MJ/m^3	Source
Light–weight blocks	United Kingdom	1000–2000[a]	Rankin, 1976
Light–weight aerated blocks	United Kingdom	1000–2000[a]	Rankin, 1976
Hollow block[b]	United States	2000–2500	Stein, 1981
Aerated block	Germany	1700	Rai, 1984
Light–weight aggregate blocks	Germany	1700	Rai, 1984

Notes:

a/ Excludes transport of blocks to site

b/ Dense aggregate hollow block

Figure 2.14. In volcanic areas, lime–trass blocks can be made with properties similar to concrete blocks, but eliminating the need for cement altogether. These blocks are made from a mix of 1 part lime to 5 trass, and they use less energy than concrete blocks (Bandung, Indonesia).

Timber–based panels are made in industrial processes which involve preparation, drying, resin bonding, and pressing. The products may be made in the country of origin or the importing country, and the level of technology varies from semi–manual to highly automated processes.

Some examples of the primary energy requirements for sawn timber and timber panels are shown in table 2.13, including transport to the sawmills and factories. In some cases these include transport to the site as indicated, showing that this is the principal component of the energy requirement for timber. The difference between the figures given for the United Kingdom which imports timber, and the United States and Australia, where it is available locally, indicates that up to 75 per cent of the primary energy requirement of timber can be due to transport.

In some analyses of the energy costs of timber, its calorific value as a fuel is added, on the grounds that its use as a building material denies its use as fuel to some other user. In practice there is little competition in the case of sawn timber between the two uses, as timber used for structural purposes is normally grown for this purpose, and is not used for firewood. Thus the calorific values are not included in the energy requirements given in table 2.13. However, there is competition between construction and fuel uses for the waste timber produced by sawmills which can be used for particle board or for fuel. It is therefore interesting to note that the addition of the calorific value of the timber would add about 15 GJ/ton to all the energy costs in table 2.13, and would put timber among the high energy materials.

Although its total energy content is not great compared with that of other manufactured building materials, such as steel and concrete, there is still some scope for the reduction in energy consumption in the processing of timber. The principal one is through the use of solar driers in seasoning. A number of designs have been proposed.[39] These are faster than air drying, but not as fast as conventional kiln seasoning, and are most profitable for slow−drying high value woods which cannot be dried fast by conventional kilns.[40]

39/ Plumtre, 1985.

40/ UNCHS, 1988.

As far as the building industry is concerned the principal ways in which the energy requirement for timber can be reduced is by increasing its life through proper preservative treatment, by reducing waste of timber in the construction process (for example, in formwork reuse), and by designing for recycling and reuse of the timber after the lifetime of one building.

Table 2.13. Energy requirements for timber production

Product	Energy requirement		Source of data
	(GJ/ton)	(GJ/m^3)	
Softwood framing, USA[a]	0.7	0.34	Stein
Timber at site, Australia[a]	2.0		Lawson
Timber processing, Argentina	0.4		Rai
Timber, Germany	1.04		Rai
Timber (concrete formwork), UK	1.6		Haseltine
Timber products, UK	5.4		Gartner and Rankin
Particle board, India	3.1		Rai
Particle board, USA[a]	9.2	4.6	Stein
Plywood, USA[a]	13		Stein

a/ Includes transport to site.

Other vegetable materials

Grass, palm leaves and other agricultural by−products are widely used as building materials, particularly for thatching. The harvesting, preparation and laying of thatch are craft processes which involve only hand tools. Thus they are practically zero−energy materials (see figure 2.15).

Extending the use of thatching in building is thus a way of reducing overall energy consumption, but this requires overcoming some obstacles to the wider use of thatch, including:

• The need for regular maintenance and replacement
• The fire risk
• Low status of thatch

A number of good guides to the construction of good quality thatch buildings are now available.[41]

41/ Hall, 1988.

2.10 Scale, location and transport energy

The discussion of the individual materials has indicated that transport energy can be a significant component of the total embodied energy of building materials at site. The contribution of transport energy is larger for those materials, such as stone and timber which have a low process energy requirement. Evidently, it will also be greater as the transport distance to site increases, and particularly large for materials which are transported internationally.

The transport energy is very significantly affected by the mode of transport adopted. Table 2.14 shows some typical figures for the transport energy requirements, per ton per km distance, for the different modes of transport. It will be noted that transport by truck is over three times more costly, in energy terms, than transport by train or river boat; transport by sea−freighter costs only 1/30th that by truck. Transport energy costs are steadily declining with the development of more efficient engines and vehicles.

Clearly, it is important for transport energy to be reduced as far as possible. But this has to be considered in the light of the total energy requirement at site. In many processes there are significant economies of scale in the use of process energy, which tend to encourage the use of large−scale production plants. In Portland cement production for instance, it has been estimated that the process energy of production at a scale of 2000 tons per day is about 12 per cent less than that of production at a scale of 100 tons per day. Similar calculations have been made in relation to the production of bricks.

Table 2.14. Freight transport energy intensities

Mode	Energy intensity (UK[a])	MJ/ton/km (India[b])
Truck	2.5	2.85
Van[c]	47.2	–
Rail	0.5	0.9
Water:		
Sea	0.7	0.09
Inland		0.9
Pipeline	0.18	

Notes:

a/ From Bending and Eden, 1984 (delivered energy).

b/ From Rai, 1986 (primary energy interest investment energy).

c/ Goods vehicle with unladen weight less than 1.5 tons.

Figure 2.15. In many areas there are existing traditions of high−quality thatched roofs. Thatch is an almost zero−energy roofing material (Central Zambia).

But where production plants are large, they have to supply a large region, and this increases the transport cost and energy at site. Thus there are trade−offs to be made between the costs (and energy costs) of production, and those associated with transport, in determining which plant size is appropriate for any region. The manufacturing technologies in use in the industrialized countries have been developed for situations where the intensity of demand is high, and consequently even a large plant supplies a relatively small region. In the United Kingdom, for example, where cement consumption per capita is about 240 kg/capita per year, there are about the same number of large cement factories as in India a very much larger geographical area, where consumption is only 35 kg/capita.[42] Thus transportation distances are, on average much greater in India than in the United Kingdom which is reflected in the total energy requirement for cement produced by these plants. This has stimulated the development of small cement plants in India, which are able to supply a smaller region (remote from an existing cement plant) and also reduce total cost and energy cost. The relative costs are shown in table 2.2.

42/ Sinha, 1990.

Optimizing the total energy cost at site can therefore contribute an important argument for the use of smaller scale manufacturing plants in developing countries to meet the national or a local market, even if the process energy costs are higher. The benefits in terms of reduced transportation energy are increased where:

- The process energy costs are low (sand, earth, timber−based materials),
- Transport is by truck − particularly energy−intensive in hilly country or where roads are poor
- The demand per head of the population is low
- Population density is low

Figure 2.17 illustrates these arguments. It shows that to minimize overall energy cost the process energy cost can be increased by an amount, which can be calculated from the consumption density of the material, the average transportation distance from the production plant to site, and the mode of transport used. In a situation like rural areas in the United Republic of Tanzania, where demand is low, where population is scattered, and where roads are poor and truck transport very costly in energy terms, it is possible for the process energy to be several times higher than in a conventional plant, if production is scattered in small−scale plants to reduce transport distance.

Figure 2.16. Rice−husk ash can be used as a pozzolanic additive to mortars and plasters, reducing the need for cement, and lowering the embodied energy requirement (Yogjakarta, Indonesia).

This graph is of course illustrative only, and there are many additional constraints to be considered; but it does indicate the importance of considering the links between, scale and location of production and transport costs in looking for ways to optimise energy costs as a whole.

2.11 The scope for recycling

The previous sections have revealed that recycling is a possible and desirable way of reducing energy consumption in the manufacture of most building materials. There are several different types of recycling opportunity which have been described.

The most immediate is the reutilization within the production process of waste material generated by the production process. Wastes of metal, glass and limestone may be returned to the process, thus reducing the energy requirement associated with these inputs. Timber off−cuts from sawmills are used in the manufacture of chipboard and particle board. Although this type of recycling is already quite widely used there are often opportunities to increase it.

A second type of recycling is used in several process industries, where products made from the material are returned to the plant as scrap at the end of their useful life, and are used in place of the unprocessed raw material as inputs to the production process. This occurs in the metal industries, steel, aluminium, copper and lead, and such secondary processing is in most cases much less energy−intensive than production from ores. Plants which carry out only secondary processing can be built, often at much lower capital cost than primary processing plants, and these may be a particularly attractive way for developing countries to recycle metals previously imported in the form of fabricated goods, and to reduce their imports of primary metals. Clearly, because transport distances are long, it is less attractive to return scrap to the exporting country, but there is nevertheless a substantial international trade in scrap.

Scrap glass can also be returned to be remelted in the production of glass, and although this does not create the same energy saving as the recycling of metals, it makes a growing contribution to the materials input to glass manufacture. Plastics can also be recycled with considerable energy saving.

A third type of recycling is that in which use is made of the waste products of other industries in the production of building materials. Blast−furnace slag from iron and steel production is a very valuable raw material in cement production, as it can be blended with the cement clinker, replacing 60 per cent of the cement, thus substantially reducing the kiln energy required. Pulverized fuel ash from coal−fired power stations can also be blended − in a proportion of up to 25 per cent − in the manufacture of Portland pozzolana cement.

Waste sulphur from chimney stacks or other industrial processes can be used to manufacture gypsum plaster and related products; lime sludge can be utilized to manufacture building lime. Pfa, slag and other industrial wastes can also be used as aggregates in concrete or in concrete−block manufacture, and indeed there are very few solid industrial wastes which have not been used for this purpose.

Wastes can also contribute directly to the energy requirements of processing. Where these wastes have some combustible material – even a small proportion – they can often be mixed with the clay material used in the production of bricks, thus replacing a proportion of the kiln fuel. Both pfa and rice husk ash, reclaimed from the use of rice husk as a fuel in the processing of rice (see figure 2.16), have been used in this way.

Agricultural wastes with a higher calorific value, for example rice husk, bagasse from sugar manufacture, sawdust from sawmills, and coconut shells, can frequently be used as fuels for burning building materials, particularly small–scale manufacture of bricks and tiles and lime. Combustible urban and industrial refuse has also been used as fuel in cement production. In both these examples, although the total process– energy requirement may not be reduced the need for premium fuels is replaced with much lower value alternatives.

Yet another form of recycling has been proposed and attempted in a limited way, but is not yet widespread. The packaging required for the transporting of manufactured goods constitutes a large and continuously increasing stream of waste material. It has been estimated that in industrialized societies the total tonnage of this waste is comparable to the total tonnage of building materials manufactured for the housing sector. In developing countries, much of this waste, often imported, finds some sort of use in the informal housing or industrial sector, and indeed much informal housing depends on it.

However, the design of this packaging takes no account of its potential for reuse in building. There is considerable potential for designing the packaging material to enhance it recycling utility for eventual use in building. Oil drums, containers, wooden packing cases, bottles, even cardboard and plastics all have some reuse potential but could be designed to have a much higher value reuse potential. The WOBO[43] was a bottle designed for a major brewing company in the 1960s which had a shape which enabled it to be converted into a building block once empty. About 50,000 were produced, but the project was not taken up on a large scale and no similar attempt has been made by a large industrial company. But the potential still exists, as shown by the large amounts of packing material

43/ Pawley, 1975.

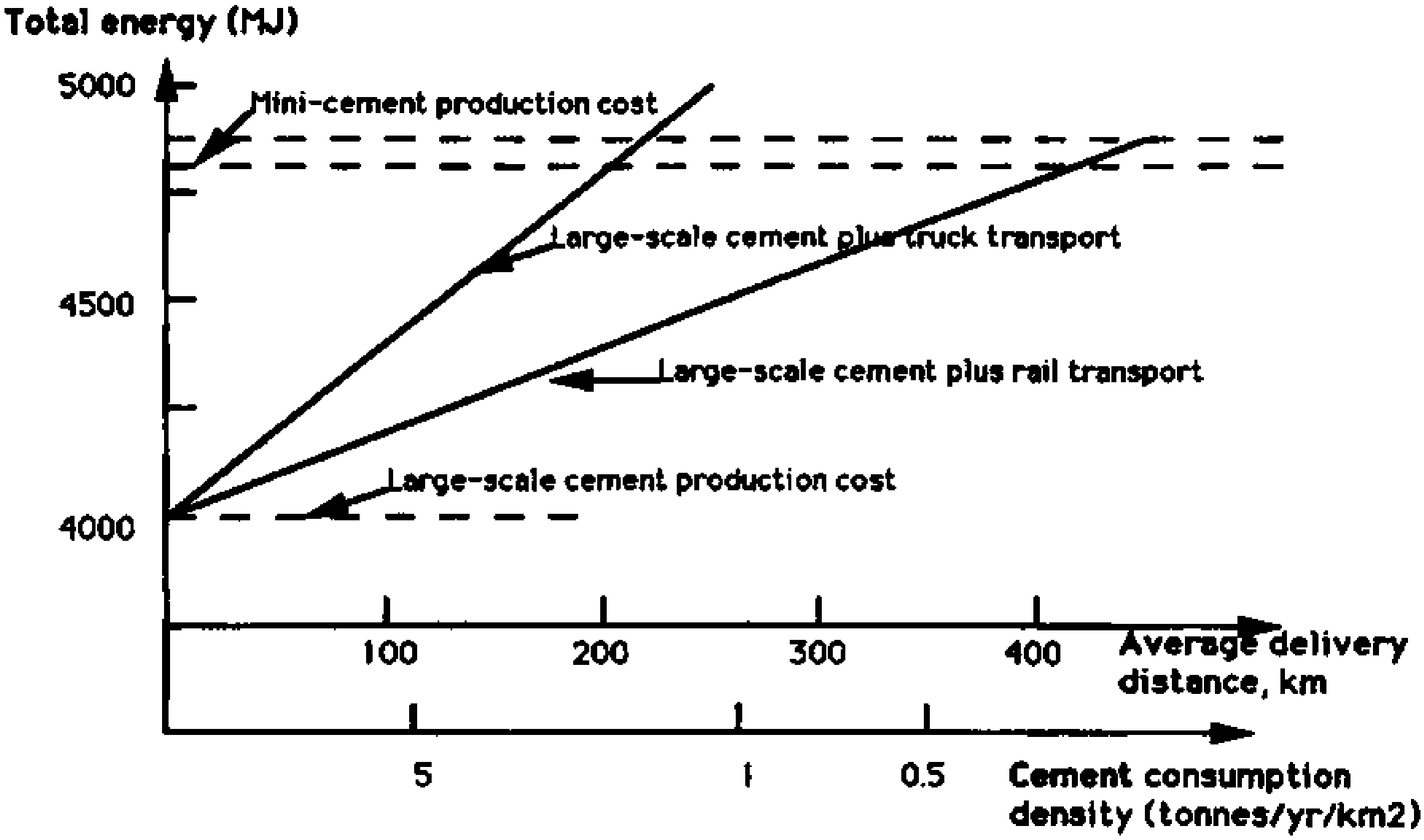

Figure 2.17. Small–scale plants use more energy in production than large plants, but if the transport distance needed for the large plant is very great, the overall energy requirement for small–scale production may be less and other wastes which are today being burnt or used as landfill. There is an urgent need to find yet more ways to convert this growing volume of waste into materials for the world's housing.

Further opportunities for the use of building materials in the construction process itself are discussed in section 3.9.

III. The energy content of buildings and building components

3.1 Introduction

The information collected in chapter II on the embodied energy content of different building materials is valuable in indicating the range of possible values for any one material, and suggesting which are low−energy and which are high−energy materials. It also helps to identify opportunities for manufacturers to save energy. But since all materials have different properties, it is rarely possible to substitute one ton (or cubic metre) of one material for another. So a simple comparison of energy contents of building materials does not help the building designer to identify opportunities for saving energy through choice of materials.

What designers need to know is how energy can be saved by the selection of one building assembly, building component or complete building system rather than another, when both alternative systems can satisfy all the simultaneous physical requirements − in terms of strength, stiffness, thermal performance and so on − of the building, and have comparable costs. This chapter assembles and discusses this information.

An interesting simplified perspective on the energy efficiency of different materials in relation to performance is given by comparing the energy costs of obtaining one unit of some property the building designer is interested in using a range of materials. For use as structural materials, it is the stiffness of the material which is of greatest importance, since this governs both the deflection of beams and slabs and the buckling of columns. Knowing the energy cost per unit volume and the stiffness coefficient (elastic modulus) of the material a comparison can be made of the energy cost of different materials per unit of stiffness. Table 3.1 shows some typical figures for a range of commonly used materials. They show that, in these terms, timber is the most energy−efficient commonly used material for use in structures, being several times more efficient than steel or reinforced concrete. They also show that the use of aluminium for structural purposes is extremely expensive in terms of energy utilization; thus where aluminium is preferred to other materials for some reason (such as for instance, its resistance to corrosion) there is a heavy energy cost penalty to be paid.

Other materials are used primarily, or in part, for the thermal resistance they offer. Materials used in external walls, cladding and insulation all need to be evaluated in terms of their thermal resistivity − how much energy is needed to save energy? The energy costs of different materials, per unit of thermal resistivity, are shown in table 3.2 The range is even higher than the range of structural costs, but again the materials at the higher energy end would be used because of other advantages they offer − durability, transparency and so on. Moreover some of the materials at the lower end are associated with other hazards − polystyrene with CFCs, glass wool with possible health risk. The issue of choice of materials is much more complex than such simple tables show, and the subject of trade−offs between energy costs of materials and energy savings has to be considered in the context of the lifetime energy costs of buildings. But these tables are useful in indicating the energy cost penalties which are associated with particular materials.

A more directly useful comparison is that between different building components or assemblies which may be directly substituted for one another. In making such comparisons, the total energy cost of the final completed assembly needs to be considered. This has to include

- Energy costs of the manufactured materials
- Transport of the materials to site
- Energy costs of the construction operation

The energy costs of the construction process include those of operating plant and machinery, heating, lighting, temporary works, and transport within the site. For high−energy materials, these costs amount to only a small proportion of the energy costs of the manufactured materials, but for low−energy materials they may be a very significant element of the energy cost.

Some comparative studies of alternative building assemblies ignore these costs on the grounds that they will be much the same whichever alternative is used. In other cases an energy overhead is added, which is a constant amount per unit area of completed building of a particular type. Table 3.3 shows for instance the energy estimates (in addition to the energy costs of the materials themselves) for a range of building types. In this case direct energy refers to all the energy used directly in the construction process; the overhead represents the energy associated with all the goods and services provided by the contractor which are nor directly incorporated into the building. Typically the construction energy, which is the sum of these two components may account for 15 to 35 per cent of the total embodied energy.

Table 3.1. Energy requirement for one unit of stiffness of different materials (after Biggs)

Material	Elastic modulus, E (MN/m^2)	Density (kg/m^3)	Energy (kj/kg)	Energy cost of one unit of E
Timber (sawn)	110 000	500	1 170	53
Mass concrete	14 000	2 400	720	124
Brick	30 000	1 800	2 800	167
Reinforced concrete	2 700	24 000	8 300	738
Steel	210 000	7 800	43 000	1 598
Aluminium	70 000	2 700	238 000	9 180

Table 3.2. Energy requirement to obtain one unit of thermal resistivity of different materials (after Biggs, 1991)

Material	Resistivity, r (MK/W)	Bulk density (Kg/m^3)	Energy (KJ/kg)	Cost of one unit of resistivity (KJ)
Foamed polystyrene	29.4	25	120 000	74
Glass wool	23.8	145	150 000	91
Timber (softwood)	7.7	500	1 170	110
Gypsum plaster	2.7	1 200	1 800	800
Light−weight concrete	0.7	1 200	720	1 252
Mass concrete	0.48	2 400	720	3 600
Glass	0.95	2 500	15 000	3 947
Rigid PVC	6.2	1 350	116 000	25 270

In the following sections some comparisons are presented between the energy costs of different building components, elements and assemblies. In each case the idea is to compare alternatives of comparable performance in other respects, and of roughly comparable costs. The materials energy cost data used in each set of comparisons are from a consistent source, which has been indicated. But because the relative costs of materials vary from place to place, and through time, the relative rankings of the assemblies in terms of energy costs are not universally valid. To determine the most energy−efficient form of construction in any particular situation, designers will therefore need to perform similar comparisons using locally relevant data. Methods for doing this are explained in chapter IV.

Table 3.3. Energy costs of construction process for different types of building (after Stein 1981)

Type of construction	Direct energy (MJ/m^2)	Overhead (MJ/m^2)	Total (MJ/m^2)
Residential, one−family	422	262	684
Residential, high−rise apartments	695	239	934
Hotels and motels	1 117	422	1 539
Industrial buildings	673	139	810
Office buildings	1 824	581	2 405
Shops and restaurants	1 128	330	1 458

3.2 Walling materials

The choice of walling system offers one major way in which designers can influence the total embodied energy content of a building, because the walls constitute most of the mass of a building, and therefore most of the embodied energy. Figures 3.1 to 3.5 show some of the alternatives in use, which vary very widely in their embodied energy requirements. This section presents three analyses of alternative walling assemblies. The first is a comparison of the costs of a single leaf brick or block wall, laid up in mortar, with the cost of a timber stud wall of the same thickness. The second compares the energy costs of complete domestic wall systems. The third compares alternative cladding systems for commercial buildings.

Figure 3.1. Rammed earth is a walling technique still widely used in the Andes and elsewhere. It provides excellent insulation with very little embodiment of purchased energy.

Figure 3.2. Where timber–frame housing is traditionally used, it has a very much lower energy requirement than walling using brick or concrete–block masonry (Viet Nam).

Figure 3.3. Housing built using cement−plastered concrete−block masonry with sheet roofs supported on steel roof joists is exceptionally energy−intensive compared with alternatives of comparable standard, but is still often used in public housing projects (Nairobi, Kenya).

Figure 3.4. Low−cost houses using stabilized−soil walls. The blocks were made by the families who built the houses and were stabilized with 4 per cent cement. Even though left unrendered there was no sign of deterioration after eight years (Kafue, Zambia).

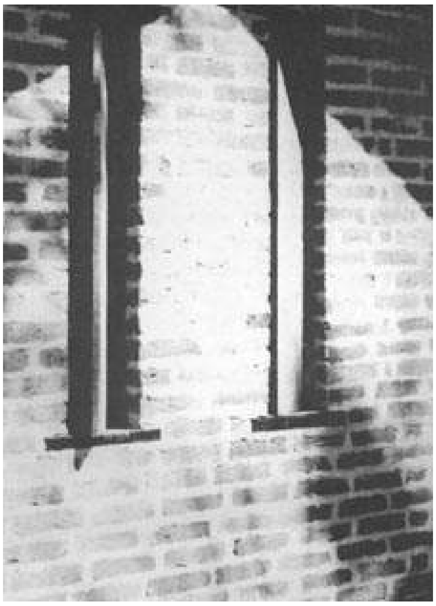

Figure 3.5. Brick walls can be an energy−efficient way to build in hot humid areas if only 100−mm thickness is used and they are not plastered. Small centre pivot windows such as these can be built using small offcuts of timber, thus saving energy by reducing waste.

Table 3.4, which is based on Indian data,[44] indicates the differences in embodied energy content of complete wall systems using different materials. The walls compared are all of roughly 100−mm thickness, which are suitable for use as internal loadbearing partitions in single−or two−storey housing. The five "walls compared have embodied energy contents which vary over a remarkably wide range. Of the four masonry materials studied, the embodied energy requirement follows the relative energy requirement of the masonry material. Burnt clay brick uses the most energy; concrete block (whether these are aerated blocks or hollow blocks of dense aggregates) uses about half as much energy as bricks; stone masonry uses still less energy, about 20 per cent less than concrete blocks in this case; while at the other end of the scale timber uses only 5 per cent of the energy required for the brick wall.

44/ From Rai, 1986.

Table 3.4. Comparative energy requirements of different internal walling assemblies, India (after Rai)

Wall assembly	Material	Unit	Quantity	MJ/unit	MJ	Total energy MJ	Rel. (percentage)
Solid brick 115 mm, plastered both sides	Bricks	Number	56	4.27	239		
	Cement	Bag	0,47	4.00	191		
	Sand	m^3	0,07			430	100
Hollow−concrete block, 100 mm, plastered both sides	Cement	Bag	0.42	400	170		
	Sand and aggregate	m^3	0.07	420	30		
	Lime	m^3	0.005	7000	35	235	55
Aerated−concrete block, 100 mm, plastered both sides	Cement	Bag	0.40	400	162		
	Sand	m^3	0.36				
	Lime	m^3	0.005	7000	35	197	46
Stone masonry, 100 mm, plastered both sides	Cement	Bag	0.385	157			
	Sand	m^3	0.34				
	Aggregate	m^3	0.05	420	21		
	Stone	m^3				178	41
Timber framework with plywood panel	Timber	m^3	0.0042	0.81	0.34		
	Plywood						
	sheets	m^3	2	10.4	20.4	21	5

This example clearly shows the large energy savings which are possible through using timber as a structural material. Against this it needs to be remembered that timber walls are not always as durable as masonry walls. They will certainly need maintenance, and may have a shorter life. In this example the basic energy cost for timber (less than 100 MJ/m^3) reflects the fact that timber is a locally grown product and that the processing involved uses mainly manual labour. But even where the energy cost per unit of timber is much higher (it could be as high as 2000 MJ/m^3 in a country which was using imported timber produced by mechanised processes), the embodied energy would still be lower than for a masonry wall. In the Indian example, the energy cost of sand is also much lower than it might be elsewhere, because it is a local material the production of which involves mainly manual labour.

All of the materials compared in table 3.4 can also be used for external walls as well, but there will often need to be an external skin to provide for weather resistance and thermal insulation. Table 3.5 compares the relative energy requirements of three commonly used different external walling assemblies. In all three cases, the loadbearing skin is of timber framing, but the external cladding and lining elements of the assembly vary. In all three cases the thermal resistivity of the total assembly is roughly the same (U−value between 1.4 and 1.9[45]), without the use of added cavity−fill insulation materials. Again, the total energy content varies over a very wide range. In this case burnt brick again is the most energy−intensive option; metal cladding (here aluminium siding with increased thickness of plasterboard to compensate for the low thermal resistivity of the aluminium) has about half of the total embodied energy. The assembly with timber cladding, here in the form of 12.5 mm thick timber shingles, has only 17 per cent of the embodied energy of the brick option. This is an important observation, because brick cladding is often preferred to other external cladding materials because of its appearance. In financial cost terms the price may not be very great, but in energy terms it is substantial.

45/ In W/m^2/degree K.

Table 3.5. Comparative energy requirements of different external walling assemblies, United States of America

Wall assembly	Material	Energy BTu/ft^2	Energy MJ/m^2	Total MJ/m^2	Rel (percentage)
Brick on timber frame walls (U = 1.4)	Brick, 100 mm	131 000	1 494		
	Building paper	1 050	12		
	Plywood. 10 mm	5 790	66		
	Timber framing	2 080	24		
	Plasterboard (10 mm)	5 300	60	1 656	100
Wood shingles on timber frame walls (U.1.5)	Shingles. 12.5 m^2	7 320	83		
	Building paper	1 050	12		
	Plywood, 12.5 mm	7 710	88		
	Timber framing	2 080	24		
	Plasterboard	6 980	80	287	17
Aluminium siding on timber frame walls (U = 1.9)	Aluminium siding	53 400	609		
	Building paper	1 050	12		
	Plywood 12.5 mm	7 710	88		
	Timber framing	2 060	24		
	Plasterboard	6 980	80	813	49

The third comparison of walling systems (see table 3.6) is between assemblies used for external cladding systems for multi−storey construction, which could be either for housing or offices. In this case it is assumed that the structure is provided by a separate assembly. Variations are considered between different basic cladding types (infill brickwork, aluminium curtain walling, loadbearing brickwork, precast concrete), between different proportions of window opening (33 per cent and 50 per cent of the wall surface), and between different materials for the window frames (aluminium and timber).

Table 3.6. Comparative energy requirements of cladding systems in the United Kingdom (after Haseltine)

Description	Relative energy requirement
Concrete frame, aluminium windows, cavity brick wall	194
Concrete frame, aluminium curtain walling (windows 50%)	272
Concrete frame, aluminium windows (33%)	175
Concrete frame timber windows (33%)	124
Loadbearing brick, aluminium windows (33%)	151
Loadbearing brick, timber windows (33%)	100
Loadbearing cavity brick no windows	143
Concrete frame, aluminium windows (33%) precast concrete cladding	287
Precast concrete cladding, no windows	324

The results of the study are presented as energy cost indices relative to the lowest energy solution. The embodied energy costs in this comparison were found to range over a factor of 3. The best was found to be the loadbearing brick wall with small timber frame windows. Increasing the amount of the window opening from 33 per cent to 50 per cent had little effect on the overall energy. Simply replacing timber with aluminium frame windows increased the energy content by 50 per cent. Replacing loadbearing brick with brick infill increased the energy requirement by 24 per cent, but replacing it with either precast concrete cladding or aluminium curtain walling resulted in overall energy costs between 2.5 and 3.25 times the cheapest system. These comparisons do not take account of the additional energy costs of maintenance and replacement which timber may require, but even allowing for this they provide further evidence, of the energy savings possible through using timber. They also show that for high−rise buildings clay bricks, which are very energy−intensive in low−rise construction, can be energy−efficient compared with alternative solutions.

3.3 Flooring and roofing materials

Flooring and roofing systems form the second largest component of the structure of any building, and thus contribute a second large component to its embodied energy. Again, a very wide range of options is available, with very different levels of embodied energy. Figures 3.6 to 3.9 illustrate some of these options. This section presents comparisons between different assemblies for horizontal spanning systems: flooring and roofing. The first of these compares alternatives for a pitched roof and is based on data for small buildings in Africa. The second compares concrete−based systems for flooring and flat roofing from Indian data. The third compares commercial flooring systems using steel and concrete.

Table 3.7. Comparative energy requirements of alternative roofing assemblies for a pitched roof (per m^2)

Option	Material	Unit	Quantity	MJ/unit	MJ	Total
Corrugated galvanized−iron sheets (30 gauge)	Sheets	kg	10	60	600	
	Timber	m^3	.009	500	5	605
Clay tiles (12.5 mm)	Clay tiles	kg	50	3	150	
	Timber	m^3	015	500	7.5	158
Concrete tiles (12.5 mm)	Cement	kg	8	8	64	
	Sand/agg	kg	32	0.1	3.2	
	Timber	m^3	010	500	5.0	72
Fibre−concrete tiles (7 mm)	Cement	kg	5	8	40	
	Sand/agg	kg	16	0.1	1.6	
	Fibres	kg	25			
	Timber	m^3	008	500	446	

For many small buildings all over the world, the roof is the major item of expenditure and several options are available. These commonly include corrugated galvanized−iron (cgi) sheets and clay tiles, and may also include concrete tiles. In some areas production of fibre−concrete tiles has recently been established, and these are rapidly gaining in popularity as a low−cost option. Table 3.7 compares these three options. The options all have a different weight, so the embodied energy in the supporting roof structure has been added. It will be seen that the energy requirements vary over a wide range. The cgi sheets with an energy intensity of over 600 MJ/m^2 have by far the largest energy requirement. Clay tiles require little more than 25 per cent of this energy. Concrete tiles use even less energy, and the fibre−concrete tiles, because they can be made thinner (7 mm is the standard thickness) use the least energy of all the options. There are a number of other considerations including durability and insulation value. On both of these, experience shows that the least energy option, fibre−concrete tiles, is at least as good as the most energy intensive, cgi sheet.

Figure 3.6. Fibre−concrete tiles are one of the most energy−efficient of the permanent roofing materials. They can be made on a small scale with little equipment and no purchased power.

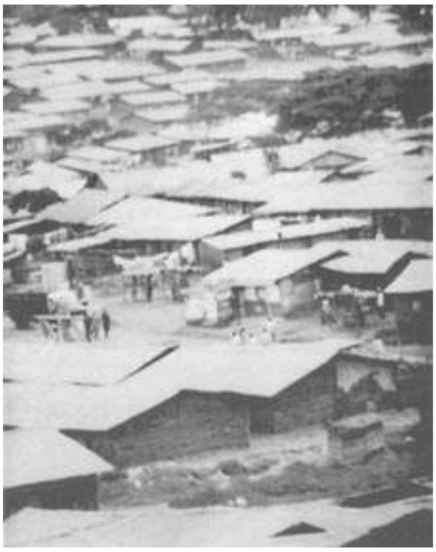

Figure 3.7. Steel sheets, even though thin and light in weight, embody a considerable amount of energy. They have an energy content per unit area of roof over 15 times that of fibre−concrete tiles.

Figure 3.8. Clay tiles are simple to manufacture, but the energy required for firing them makes them more energy−intensive, per area of roof, than concrete of fibre−concrete tiles.

Figure 3.9. Houses with thatched roofs and earthwalls have a very low energy content, but require frequent maintenance. Replacing such houses by houses built of materials with better durability has the effect of greatly increasing the embodied energy used (Kerala, India).

Table 3.8. Comparative energy cost of flat roofing systems (per m², assuming 3.5 m span)

System	Unit	Quantity	MJ/unit	MJ	Total	Relative
Rein forced−concrete slab:						
Cement	Bag	0.81	400	324		
Sand	m³	0.06		4		
Coarse aggregate	m³	0.10		43		
Steel	kg	5.7		151	522	100
Reinforced−brick− concrete slab:						
Cement	Bag	0.53		212		
Sand	m³	0.04	400	3		
Coarse aggregate	m³	0.06		26		
Bricks	Number	26		115		
Steel	kg	5.04		133	489	94
Cored concrete unit:						
Cement	Bag	0.61		244		
Sand	m³	0.04	400	3		
Coarse aggregate	m³	0.08		35		
Steel	kg	5.47		145	427	82
Channel concrete unit:						
Cement	Bag	0.46				
Sand	m³	0.03	188	2		
Coarse aggregate	m³	0.06	26			
Steel	kg	5.35		141	357	68

Table 3.8 compares four different flat roofing systems commonly used in India. The unit of comparison here is simply between the structural part of the roof, assuming a one−way span of 3.5 m. Each roof would be completed with a screed and waterproofing membrane and also some insulation, but these are more or less the same whichever system is used. The total energy requirement of each system is calculated and its value relative to the basic system, a solid reinforced−concrete slab, is also shown. All four of these systems are based on reinforced concrete, so the range of energy requirements is not so wide as the walling comparisons. The reinforced−brick−concrete slab differs from the solid concrete slab in using burnt−clay bricks as fillers in the lower part of the slab. This saves some energy in replacing part of the concrete with lower−energy bricks, and as it is also lighter, so it saves some reinforcing steel. The overall reduction in energy cost is not great, however. The use of precast−concrete slabs is more efficient. These are profiled (either cored or channel shaped) in such a way as to require considerably less concrete than the solid slab; as they are lighter they

also use less reinforcement, although some steel extra to the spanning requirement is needed to prevent damage during transport. The lowest cost solution uses 68 per cent of the energy required for a solid slab.

Table 3.9 compares two systems for a fireproof flooring for commercial construction, based on a 9 m square bay size. The first system is the cheapest *in−situ* concrete system, using a waffle slab, 400 mm deep; the second system is a steel frame construction with corrugated steel decking and a concrete fill. Gypsum plasterboard is used for fireproofing. The two systems have approximately the same financial costs. The steel system requires 65 per cent more energy than the concrete system. It can be shown that the difference between the energy requirements of these two systems is greater than one years typical energy consumption in the amount of office space provided.

Table 3.9. Comparative energy requirements of different office flooring system: based on a 9 m square bay (after Stein 1981)

Floor system	Material (unit)	Quantity	GJ/unit	GJ	Total GJ
Reinforced concrete waffle slabs	Concrete (m^3)	20.1	3.62	72.7	
	Reinforcement (kg)	1970	0.036	17.7	
	Mesh (kg)	319	0.056	17.9	162.3
Steel girders with concrete deck	Concrete (m^3)	8.4	3.62	30.4	
	Structural steel (kg)	3182	0.052	167.6	
	Steel deck (kg)	879	0.064	56.8	
	Mesh (kg)	122	0.056	6.9	
	Misc			7.8	269.5

3.4 Alternative cementitious binders

Mortars, plasters and low strength concretes comprise a significant part of the material requirements for any small building whether masonry or concrete frame systems are used. There are a variety of alternative mortar mixes which can be used, using cement, lime and pozzolanic materials. Cement is often in short supply, and in some cases mortars based on lime, which can be manufactured in small rural kilns, and pozzolanic materials such as pfa (pulverized fuel ash) and rice−husk ash, can often be used instead. Pozzolanic materials can also be used to replace a part of the cement used in cement−based mortars. The use of such pozzolanas looks particularly attractive from an energy point of view, because they are waste materials, and the energy costs involved are, therefore, limited to transport energy.

Table 3.10. Comparative energy requirements of alternative mortars (based on 1 m^3 of wet mortar

Mortar type		Unit	Quantity	MJ/quantity	MJ	Total	Relative
Cement:sand (1:6)	Cement	ton	0.25	8 096	2 024		
	Sand	m^3	1.07	100	107	2 131	100
Cement:lime:sand (1:1:6)	Cement	ton	0.250	8 096	2 024		
	Lime	ton	0.113	5 600	630		
	Sand	m^3	1.07	100	107	2 761	129
Lime:surkhi (1:2)	Lime	ton	0.301	6 300	1 911		
	Surkhi	ton	1.140	1 122	1 571	3 482	163
Lime:surkhi:sand (1:1:1)	Lime	ton	0.301	6 300	1 911		
	Surkhi	ton	0.570	1 122	785		
	Sand	m^3	0.475	100	48	2 598	122
Lime:rha:sand (1:1:1)	Lime	ton	.309	6 300	1 911		
	rha	ton	0.57	100	57		
	Sand	m^3	0.475	100	48	2 016	95
Cement:pfa:sand (3:4:6)	Cement	ton	.19	8 096	1 518		
	pfa	ton	0.062	100	6		
	Sand	m^3	1.07	100	107	1 631	77

Source: Rai

Table 3.10 compares the energy requirements of 1 m^3 of mortar made by different mixes in India. The basic mortar, very widely used and specified, is a 1:6 cement:sand mortar. The mortar based purely on cement is rather harsh and brittle: a better mortar for general purposes is a cement:lime:sand mortar, 1:1:6. The lime in this mortar is in addition to the cement used in the basic mortar, so the energy required is higher. A pozzolana used in India is *surkhi*, a burnt clay pozzolana. *Surkhi* is made in a number of ways, but most commonly by burning clayey soils in a crude field kiln. The energy cost per unit weight is low, but the surkhi is of poor quality, and an acceptable mortar requires a 1:2 *surkhi*:sand mixture. This turns out to require considerably more energy than the cement sand mortar. A better quality surkhi, though a more energy−intensive one, can be used in a 1:1:1 lime: *surkhi* sand mixture. This gives an energy cost lower than the 1:2 mortar, but still more energy intensive than the cement mortar.

The use of rice−husk−ash (rha) pozzolana is however worthwhile in energy terms. The 1:1:1 lime:rha:sand mixture uses 5 per cent less energy than the basic 1:6 cement mortar. But probably the best solution in terms of energy is the replacement of 25 per cent of the cement with pfa, which reduces the energy content of the mortar mix by about 20 per cent. Where available, pfa is an almost zero−energy waste product. But this is only possible if the mortar is made with an OPC; pfa replacement is not permissible if Portland pozzolana cement is being used.

The general conclusion from this example, based on Indian data, is that the energy savings from replacing cement mortars with available mortars are rather little. This conclusion may not, however, hold in other locations where relative energy costs of cement and alternatives may be different.

3.5 Embodied energy in complete building systems

To compare alternative entire construction systems and to get an idea of how the embodied energy in a building is distributed among the various constructional elements of a building, it is useful to look at the overall embodied energy of complete building systems. This section looks at several comparisons which have been made for different countries, for residential and non−residential buildings. Figure 3.10 illustrates some of the options.

Table 3.11 compares the energy requirements of several different alternative forms of housing construction suitable for large−scale housing projects. In this case, the embodied energy is calculated from the amount of material specified in the bill of quantity and the drawings and from the embodied primary energy contents of the individual materials. The embodied energy figures in table 3.11 do not, however, include mechanical plant or electrical systems, nor site works external to the building itself, which would not be much affected by the comparison. The energy in the construction process is also not included for the same reason. The four types of construction compared are:

Table 3.11 Comparative energy requirements of alternative housing systems (after Gartner and Rankin)

Type of housing	Concrete	Steel	Masonry	Timber	Internal	Roof finishes	Total (MJ/m^2)
Unit	**m^3**	**kg**	**m^2**	**m^3**	**m^2**	**m^2**	
Energy/unit (MJ)	1600−3000	47	100−450	2500	65	150	2
Type a: two−storey brick/block walls, tile on timber	246−317	14	364−1324	265	247	99	1235 to 2260
Type b: as type a, light−weight infill walls	213−273		384−947	265	247	99	1207 to 1831
Type c: five−storey reinforced concrete flats, floor	264−333	541	387−1298	173	273	62	1700 to 2680
Type d: Multi−storey flats	1807−2208	1904	114−331	65	272	23	4803

(a) A two−storey house of cavity wall brick and block construction, with load−bearing outer walls, timber−framed pitched roof and timber−joist upper floors;

(b) A two−storey house with load−bearing crosswalls of brick or block and with light−weight infills to outer panels. Floors and roofs similar to type (a);

(c) A five−storey block of flats with load−bearing walls of brick or block, reinforced−concrete floors and pitched−timber frame roof;

(d) A medium− to high−rise (eight or more floors) block of flats with load−bearing walls, floor and roof slabs of reinforced concrete.

For each system the range of possible energy requirements is quite wide, reflecting different alternative materials which might be specified. The range is particularly wide for masonry walling materials, for which the energy requirement may be anything from 100 to 450 MJ per square metre of walling depending on the source and type of block used; the embodied energy in concrete is also quite variable, depending on the mix used and the source of the aggregate. Taking the mid−point of the range for each building type it can be seen (see table 3.11) that the two low−rise house types require around 1650 MJ/m^2. The increase to five storeys increases the energy requirement by nearly 50 per cent, mainly because of the need for reinforced concrete floors. But change in form of construction needed to build the high−rise apartment block increases the energy requirement by 275 per cent, because of the extensive use of reinforced concrete involved.

It is interesting to compare the total energy requirement for this example with residential energy costs from other locations. Figure 3.11 shows the breakdown of embodied energy cost of a typical two−family house, again in terms of the energy cost per unit of floorspace provided. The house in this case is a two−storey wood−frame detached house. In this case, construction, sitework and mechanical and electrical plant have all been included in the analysis. These items add up to almost exactly 50 per cent of the total embodied energy requirement of 5023 MJ/m^2. Without them, the embodied energy requirement is quite similar to the five−storey example from the United Kingdom, in spite of the very different form of construction used.

In many instances, builders in developing countries have a choice between a house made partly or wholly of manufactured materials or one using well−developed traditional building systems which can provide living standards of the same level. The house made of manufactured materials may be no more expensive, because the traditional construction process makes extensive use of manual labour. Table 3.12 shows a breakdown of the energy costs of three houses in Argentina. All three are of the same plinth area (80 m^2) and are single storey. The first is entirely built using manufactured materials: hollow−brick walls, concrete beams and columns, and prestressed−concrete system roof. The second replaces the bricks with concrete blocks in the walls, and uses galvanized−iron roof sheets for roofing, but with a concrete frame. The third uses largely local materials: adobe walls, galvanized roof sheets on timber beams and columns. The house of manufactured materials has an embodied energy per unit of floor area of about 1600 MJ/m^2, very similar to the two−storey house shown in table 3.11. Changing the roof construction lowers the energy by 17 per cent; the energy can be lowered by a further 25 per cent if local aggregates are used. Using adobe and timber in place of brick and concrete makes a very large difference to energy costs. The total now comes down to under 600 MJ/m2, only a little over one third of the energy required for the most−energy−intensive house, with a further 25 per cent reduction possible if local aggregates are used. These comparisons show that very large reductions in the energy requirements for essentially the same building are possible if traditional earth and timber−based materials are used. Conversely, it shows that as the pattern of housing construction in developing countries changes from one based largely on low−energy rural materials to one based on manufactured materials, the energy requirements rise very steeply.

Table 3.12. Comparative energy requirements for houses with different materials in Argentina

House type	Material	Unit	Quantity	Energy (MJ)	Total MJ	MJ/m^2
House 1 Made primarily with manufactured materials	Cement	kg	10 159	40 636		
	Sand	m^3	29	9 537		
	Lime	kg	279	11 511		
	Bricks/tiles	kg	21 961	51 828		
	Iron	kg	880	3 608		

	Stone	m^3	27.4	9 042		
	Windows/ doors			528	126 690	1 583
House 2 Made partly with manufactured materials	Cement	kg	14 780	59 120		
	Sand	m^3	42	13 761		
	Lime	kg	1 588	14 292		
	Iron	kg	525	2 152		
	Stone	kg	38	12 672		
	Roof sheets	m^2	96	2 640		
	Windows/ doors			528	105 165	1 314
House 3 Adobe walls, cgi sheet on timber roof	Adobe	kg	77 360	147		
	Cement	kg	5 386	21 544		
	Sand	m^3	18.5	6 105		
	Lime	kg	1 079	9 711		
	Timber	m^3	10.1	477		
	Roof sheets	m^2	96	2 640		
	Stone	m^3	18.4	6 072		
	Windows/ doors			528	47 224	590

Source: Rai.

Figure 3.10 Housing in high−rise apartment blocks is often required in crowded city locations, but uses two or three times the amount of embodied energy of the same housing build in two−storey buildings (Tianjin, China).

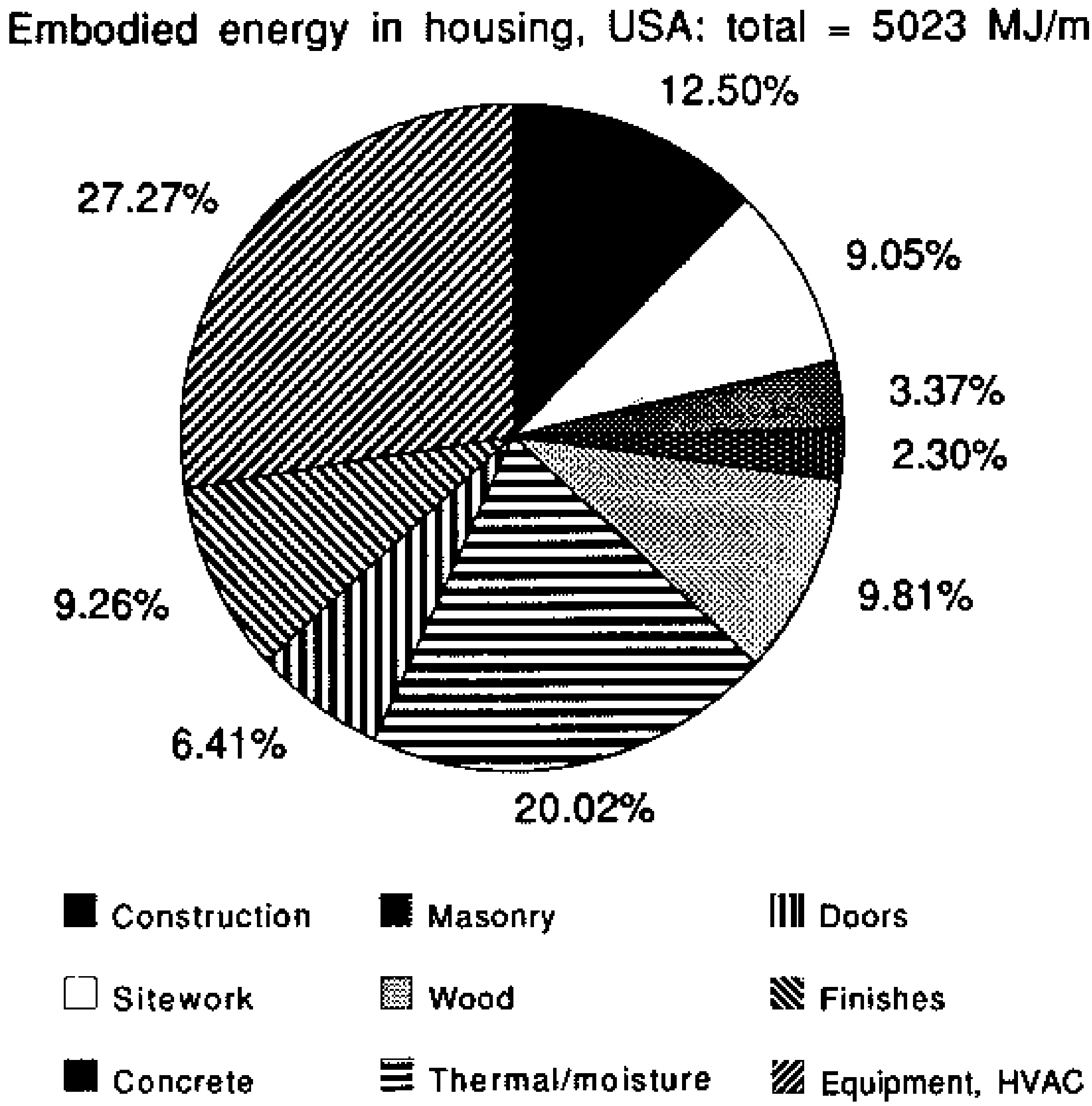

Figure 3.11. Breakdown of the embodied energy used in housing in the United States by the various materials and components. Embodied energy in housing, United States: total = 5023 MJ/m^2.

3.6 Trade−offs between direct and indirect energy costs

If design decisions are to be influenced by the need to save energy, then the total energy requirement for a building over its lifetime needs to be examined, including the energy required for the operation of heating and cooling systems, as well as that required for construction, maintenance and repair, and eventual demolition. These energy requirements can be divided into direct energy requirements (for heating and cooling), and indirect energy requirements (embodied energy plus energy for maintenance and repair and demolition). Table 3.13 shows the results of a comparison of the estimated total indirect energy requirements for different classes of buildings in Europe. The buildings were grouped by use category (single−family residences, housing, offices and industrial buildings), and the total indirect energy requirement has for each category been subdivided into subsystems (structure, insulation, exterior cladding, interior finishes, heating, plumbing, ventilation, electricity and site work). It can be seen that the structural part predominates in all categories of building, but that the next most important component depends on the use category. For single−family residences and industrial buildings the site work is second largest subsystem; for housing it is the heating and ventilating; and for offices it is the external cladding.

The total embodied energy costs for offices and single family residences are similar. Housing requires only 10 per cent less indirect energy, and industrial structures require one third less, mainly accounted for by use of lighter cladding and structure and less insulation. The ratio of indirect to direct costs is interesting. In this comparison an 80−year lifetime was assumed for all building categories, and on this basis the indirect energy constituted between 5 per cent of the total energy (for inefficient mostly office buildings) and 40 per cent for recently built low−energy buildings.

In order to understand the importance of the embodied energy in the context of the total energy consumption it is important to know how embodied energy compares with annual running energy. Several of the studies of the embodied energy in buildings have compared this energy with the direct energy costs, i.e., the annual energy consumed in the building. For the comparison to be useful, the annual running energy has to be translated into units of primary energy consumed. Table 3.14 assembles some of these data. The first two examples are from the 1970s in the United Kingdom and the United States, and are comparable. The house in the United States is larger and uses more energy in both categories. The embodied energy is about 1.5 to 2 times the annual running energy. The third house compared is from Switzerland, where insulation standards are generally better than in the United Kingdom and the United States, and is based on more recent excluded in the other two cases giving a ratio of 5.8. Excluding these items, the embodied energy is about three times the annual energy, data. In this case the embodied energy calculated includes elements of site work and mechanical equipment which were excluded in the other two cases giving a ratio of 5.8. Excluding these items, the embodied energy is about three times the annual energy.

Table 3.13. Comparative total indirect energy requirements for various types of building (after Kohler 1987)

Building type	Components	MJ/m^2	Total	Relative
Single−family residence	Structure	2088		
	Insulation	72		
	External walls	360		
	Internal finishes	648		
	HVAC	540		
	Site work	936	4644	100
Housing	Structure	1332		
	Insulation	216		
	External walls	504		
	Internal finishes	396		
	HVAC	864		
	Site work	756	4068	88
Offices	Structure	2160		
	Insulation	72		
	External walls	792		
	Internal finishes	648		
	HVAC	468		
	Site work	720	4860	1.05
Industrial	Structure	1656		
	Insulation	216		
	External walls	216		
	Internal finishes	288		
	HVAC	144		
	Site work	576	3096	0.67

Table 3.14. Ratio of embodied energy to annual energy for houses in different locations

Location	Embodied energy (E) (GJ)	Annual energy (A) (GJ)	Ratio (E/A)
United Kingdom, 1975	140 (ave)	71 (ave)	2
United States, 1981	190	119	1.6
Switzerland 1987 (m^2)	4.6	0.8	2.99
Pakistan, 1986	20−100	7.2	3 to 14

In the developed countries there has been a marked improvement in insulation standards in the last 10 years leading to a reduction in annual energy consumption, particularly for new buildings, and this trend is expected to continue. It has been estimated[46] that for low−energy buildings the indirect energy costs may amount to as much as 50 per cent of the total lifetime energy costs of the building, i.e., embodied energy in construction, maintenance and demolition will equal annual running costs over the building's entire lifetime.

46/Kohler, 1987.

In developing countries it is difficult to make accurate comparisons. Some data are available on the total energy budget of households in different locations. For Pakistan in 1986, figures indicate[47] an annual household primary energy consumption, in an area where some seasonal heating is required, of about 24 GJ.[48] Data show that the range of figures from local village surveys is extremely wide, varying from an average of 8−11 GJ per capita in Africa, 7−16 GJ per capita in India, to as high as 29 GJ per capita in Chile, a figure giving a household energy consumption considerably higher than in Europe. To produce figures comparable with those given above a number of assumptions are needed.

47/Qazi, 1989.

48/Leach, 1988.

Assume a family of five living in a house of 80 m2 in rural Pakistan, constructed with walls of burnt−clay brick and with a corrugated−steel−sheet roof. The total embodied energy in this house will be similar to the house in Argentina which is made partly of manufactured materials, i.e., about 100 MJ. Where earthen materials can be used in place of bricks and fibre−cement tiles in place of roof sheets, the embodied energy requirement for the house could be reduced to as little as 20 MJ. The annual household delivered energy budget of this family will be assumed to be 24 GJ per capita. Most of this will be assumed to be firewood, so this can be taken as the primary energy requirement. Most of this energy will however be used for cooking. Space heating will be secondary, but if the heat gains from cooking are considered it may be assumed that 30 per cent is required for space heating, i.e., space heating needs are 7.2 GJ. Embodied energy therefore constitutes about 14 times annual heating energy if the house is built with brick and steel, but only three times annual heating energy if it is made with low energy local materials.

Generally it can be seen from these rough calculations that the embodied energy becomes a more significant part of the total where:

(a) The climate is warmer;

(b) Manufactured materials are used in place of local materials;

(c) In colder climates where standards of insulation are high and heat losses are consequently low.

It is also possible to examine the trade−offs between embodied energy and annual energy consumption arising from specific modifications either to existing or projected buildings. As one example, the effect of adding insulation to two of the walling assemblies shown in table 3.15 has been calculated. The additional embodied energy can be compared with the energy saving calculated assuming a particular climate. Taking typical date for a warm temperate climate, it has been estimated that for an increase in embodied energy in the house as a whole of 7.26 MJ, an annual saving of 21.25 MJ can be made, i.e., there is a payback period in energy terms of less than four months.

A similar study has been made of the energy tradeoffs associated with the use of double and triple glazing. Table 3.16 shows the energy payback periods associated with the use of better insulated glazing; again in almost all these cases the additional energy used is regained in less than one year.

In the hot climates of many developing countries the principal energy cost in running buildings is for cooling not heating. Again, a range of investments in the building fabric can be used to reduce future cooling loads, including better insulation of roofs and walls, the use of thermal storage, and the use of courtyard layouts. Energy payback periods for these techniques can be calculated in a similar way.

Table 3.15. Trade−offs between energy costs and energy saving of insulation (after Stein)

Wall type	Annual energy requirement (MJ)	Embodied energy (MJ)	Payback period (months)

Wood shingles:			
No insulation	30.7	26.5	
90 mm insulation	9.45	33.76	
Difference	21.25	7.26	4
Brick cladding:			
No insulation	29.4	153.0	
90 mm insulation	9.33	160.4	
Difference	20.07	7.40	4.5

3.7 Design of buildings for recycling and reuse

Section 2.9 examined various possible ways to reduce the energy costs of manufactured building materials by making use of recycling as a part of the process of manufacture. Building designers can also make a large contribution to long term energy savings in two ways:

(a) Incorporating into buildings materials which have been reclaimed from the demolition of previous buildings or from other sources;

(b) Designing new buildings so that they can be recycled when they reach the end of their useful life.

Reuse of recycled elements from old buildings is often feasible where masonry and timber have been used. Fired−clay bricks or stone masonry building elements can often be reclaimed undamaged from demolished walls, particularly where soft mortars have been used. Earth from demolished adobe or rammed earth walls can be used in new walls and is preferable to newly quarried earth because it involves no digging or screening. Timber which has been treated or protected from decay can similarly often be reclaimed with a small amount of work to remove nails and ironwork.

Steel structures are more costly to demolish because joints will generally have to be cut, but steel sections can then also be reused if they are protected from corrosion. Lead and copper and even galvanized−steel roof sheeting can often be reused, though galvanized−steel sheets have a limited life. In many countries there is a well−established market in recycled or reclaimed building materials.

Table 3.16. Energy payback periods for single, double and triple glazed windows

	Single	Double	Treble
Energy payback period (years)			
Softwood frame	0.2	0.9	1.8
Hardwood frame	0.3	0.9	1.9
Aluminium frame	1.0	2.7	4.7
upvc frame	1.6	4.0	6.8
Energy payback period (years) (cf single−glazed softwood frame)			
Softwood frame	reference	0.4	0.6
Hardwood frame	infinite	0.4	0.6
Aluminium frame	infinite	0.6	1.0
upvc frame	infinite	0.7	1.2
Energy payback period (years) (cf double−glazed softwood frame)			
Softwood frame	reference	1.4	
Hardwood frame	infinite	1.5	
Aluminium frame	infinite	2.4	
upvc frame	infinite	3.1	

Source: Rai, 1991.

Reinforced concrete involves much more energy to demolish. Demolished concrete can be used as hardcore, but in this use it has a much lower value than in its former state. With some manual labour, reinforcing steel can be straightened and reused, but there will be some loss of effectiveness.

To a large extent, the use of recycling depends on the designer or builder noticing an opportunity. Secondary materials from a variety of sources outside the building industry are used in low−cost housing in cities of the developing world. Steel from the drums used for transporting oil and chemicals, plywood from packing cases, disused railway tracks and sleepers, old vehicle bodies can all be used effectively in new buildings. The embodied energy cost associated with the reuse of materials in this way can be regarded as zero since they have fulfilled the primary purpose for which they were manufactured.

Possibly the most effective form of recycling available to designers is to avoid the need for new building altogether by making adaptive reuse of entire existing buildings. Buildings in which the basic structure is sound can often be refurbished with much lower use of energy than will be needed for a new building because the structure and envelope incorporate a very high proportion of all the embodied energy. Obtaining the energy benefits of reuse may be worth some compromises in both function and location compared with the ideal new building.

The energy issues associated with deciding whether to refurbish an existing building or build a new one are illustrated in figure 3.12 which compares the total energy lifetime energy consumption over a period of years assuming four different scenarios:

(a) Continue to use existing building without improving its energy efficiency;

(b) Retrofit existing building now to improve its energy efficiency;

(c) Retrofit existing building in five years time to a higher standard;

(d) Replace the building now with a new low−energy building.

The first option is likely to lead to lower total energy only for a very short period. In the medium term, perhaps up to 20 years, the lowest energy option will be one of the retrofitted options. The last option, replacing the building with a new one, may be the least energy−efficient option if a lifetime of over 20 years, is considered. Even then a further more energy−efficient retrofit may still be possible at a later stage.

Designers of new buildings can also reduce the long−term energy requirements of the built environment by designing buildings on the assumption that they will last much longer than the current requirements of the client. Examination of the historic buildings of today's cities reveals that many buildings have over time had a variety of uses − houses are converted over their lifetime to a variety of different types of occupation; large houses can become apartment blocks, schools, offices; churches become meeting halls, sports halls and so on. An assumption of long life and a "loose fit" to existing requirements may be the best way of all for designers to reduce long−term energy costs.

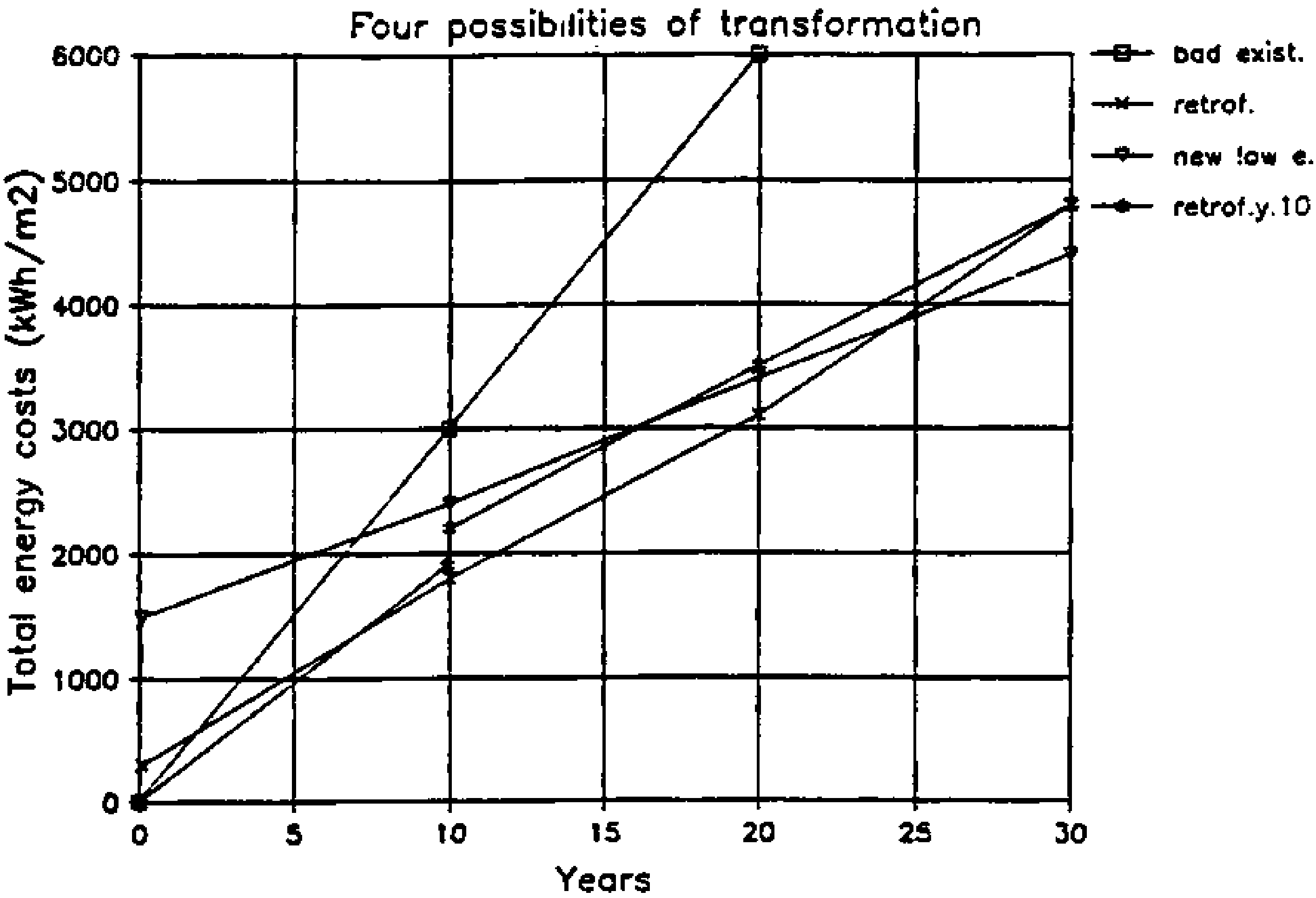

Figure 3.12. Four alternative ways of transforming an existing inefficient building and their long−term energy costs.

Buildings can also be designed so as to enable their components to be easily reclaimed if they are demolished. This will involve using materials, such as brick, stone and timber, ceramic or concrete roof tiles, which can be recycled, jointing them so that they can be reclaimed with a minimum of work, and making use of units of a size and shape which is likely to continue to be needed in the building industry. Components such as doors, windows and staircases have a particularly high recycling value. Brittle materials like glass and composites like concrete are, however, much more difficult to recycle. The use of materials like this should consequently be minimized.

IV. Strategies for optimizing energy use in the building fabric

4.1 Strategies for producers of building materials

The energy use in the production of building materials accounts for a high proportion of the total embodied energy in buildings, and thus improvement of energy use in production processes is a crucial part of any overall strategy for energy conservation in the built environment. Much of the energy use in building materials takes place in the manufacture of a few extensively used materials which involve high−temperature kiln processes, notably iron and steel, cement, clay bricks and tiles and glass, and energy−saving strategies should concentrate on these processes. A second area of significant energy use is for mechanical plant used for quarrying, conveying, crushing and grinding materials in manufacturing processes. A third is low−temperature processes such as drying and autoclaving. A fourth is in the transport of materials both from quarries to the production plant, and from the factory to the site or the local distributors.

Strategies for energy saving in building materials manufacture should therefore include:

(a) Careful study of all kiln processes to assess the energy efficiency achieved and opportunities for improved energy efficiency; replacing energy−inefficient processes with more efficient ones (such as dry process or vertical shaft kiln processes for cement production, continuous kilns in brick production – see chapter II);

(b) Examining opportunities to use cheaper or non−premium fuels in kiln processes, such as agricultural waste for brick burning, municipal waste for cement production, addition of combustible materials to clays in brick manufacture;

(c) Use of recycled materials in production processes such as scrap iron and steel, and recycled glass;

(d) Use of low−energy additives or extenders, such as pozzolanic materials or blast−furnace slag in cement production;

(e) Changing the product mix to produce a higher proportion of low−energy materials such as hollow−clay bricks rather than solid bricks;

(f) Energy auditing of all production processes to identify energy end−use patterns; upgrading or replacement of energy− inefficient plant; improving maintenance of mechanical plant;

(g) Use of grinding aids to reduce energy requirements in grinding processes;

(h) Use of solar energy or waste kiln heat in low− temperature operations such as drying (timber, bricks) or water heating;

(i) Selective replacement of mechanical equipment with efficiently used human labour, particularly for loading and unloading, and short−distance conveying;

(j) Reduction of transportation energy by appropriate location of production plants, and small−scale production.

Because of the high energy intensities of many production processes, larger producers using modern technologies (for example, cement producers) are generally keenly aware of the need for energy efficiency, and can be expected to undertake many of these measures without additional incentives, in order to reduce production costs. However, many of the producers of building materials operate at a small scale, using traditional processes and are slow to respond to changing pressures or alter established practices. Thus policy makers and government departments have a role to assist building−materials producers improve their energy efficiency in the ways such as:

(a) Supporting research into methods of improving energy efficiency of traditional energy−intensive building−materials production technologies, such as brick and tile manufacture, lime manufacture; helping to promote the transfer of improved technologies in the industry through meetings and demonstration projects;

(b) Offering incentives to producers to undertake energy audits;

(c) Supporting studies to examine the effects on materials properties of altering raw materials to reduce energy, for example the replacement of Portland cement with a Portland−pozzolana cement; helping to promote the application of low−energy materials by designers and in the construction industry.

4.2 Strategies for builders

Construction activity accounts for a small but important proportion of the embodied energy in buildings, ranging from about 15 to 35 per cent of the embodied energy. A large part of the energy use in construction is related to the use of mechanical plant for transporting, levelling, digging, lifting, compacting and mixing, while a second significant component relates to the energy use in the buildings – both temporary and permanent – used by the builder for the construction activity. Energy embodied in materials used for temporary works – scaffolding and formwork for concrete, for example –forms a third component.

Construction efficiency also, to some extent, affects the total amount of embodied energy in the building, since inefficient site management can result in considerable materials wastage. For example, it has been estimated that on typical urban construction sites in developing countries more than 25 per cent more cement is used than would be needed if quality control was improved. In other cases, excess material is used over the amount specified in the design (for example, in trench foundations) to reduce time and labour cost.

The decisions of the builder may also dictate the sources of supply of the materials used in a building, and hence determine the transport energy component of the embodied energy, which is often significant.

Thus strategies for improving energy−use efficiency in construction should include:

(a) Conducting energy audits on typical construction sites to identify energy use and energy−saving opportunities; making site staff aware of the energy implications of all site activities, and introducing incentives for energy saving;

(b) Examining the energy efficiency of all mechanical plant used; replacing inefficient plant with more efficient plant; reducing the unnecessary use of plant; ensuring that all plant is properly serviced and maintained (poor maintenance can increase energy use by 15−20 per cent); considering the selective replacement of mechanical plant with the use of manual labour;

(c) Examining energy efficiency of all buildings used in the construction process, and where appropriate, upgrading them;

(d) Examining the extent of use of transport of materials etc. to and within the site, with a view to reducing journeys and utilising the most energy−efficient means of transport available; selecting where possible only local sources of materials supply;

(e) Examining the embodied energy in temporary works, and replacing high−energy materials with lower−energy materials in temporary works where possible, for example, using timber and bamboo rather than steel for scaffolding and formwork though the total lifetime energy use will be the important standard of comparison;

(f) Looking for opportunities to save wastage of materials, such as excessive concrete in foundations, excessive cement in concrete mixes; looking for ways to reduce materials use by the use of closer supervision and quality control;

(g) Separating all waste materials generated to facilitate their recycling.

Most of these strategies will prove cost effective to implement, so it should be possible to persuade builders to implement them without additional financial incentives, once they have been identified. Nevertheless, national and local governments have a role in promoting these strategies in a number of ways, such as:

(a) Supporting research into energy consumption in the construction process;

(b) Conducting training events for builders in energy conservation;

(c) Providing incentives, where national economic considerations conflict with the financial interests of builders, to invest in energy saving through for instance replacing or upgrading inefficient plant, or through the use of manual labour in place of mechanical plant.

4.3 Strategies for designers

Over 80 per cent of the embodied energy in a building is the energy required to manufacture the materials. It has also been shown that most of this energy is used in only a small number of the materials used in building, principally iron and steel products, cement and concrete products, bricks and ceramic materials. Moreover, the embodied energy in a building amounts to several times the annual energy consumption of that same building in use. Thus designers have the opportunity to make a major contribution to the reduction of the total energy use in the built environment through strategies such as:

(a) The use of less materials, particularly high−energy materials, in building design; looking for ways to reduce the thickness of walls, finishes, storey heights etc., where this can be done without compromising other aspects of performance;[49]

(b) selection of low−energy materials rather than higher−energy alternatives when these are available. Some examples are:

(i) Use of timber in place of steel or concrete for beams and trusses;

(ii) Use of lime−pozzolana mortars in place of cement mortars;

(iii) Use of soil and stabilized−soil blocks or sand−lime bricks rather than clay bricks;

(iv) Use of light−weight, aerated, concrete blocks rather than dense concrete blocks;

(v) Use of gypsum−based plasters rather than cement−based plasters;

(c) Selection of lower−energy structural systems, such as use of load−bearing masonry in place of reinforced concrete or steel frames;

(d) Design of low−rise buildings in place of high−rise buildings wherever the situation permits

(e) Selection, where possible, of waste or recycled materials, or manufactured materials which incorporate these; for example, Portland−pozzolana cements using pfa or blast−furnace slag; asphaltic roof sheets incorporating recycled paper, building boards from agricultural waste, use of second−hand or reclaimed building materials;

(f) Design for long life and adaptability to varying requirements;

(g) design for recycling; use soft mortars which will allow bricks to be reclaimed; avoid reinforced concrete;

(h) Design for the use of materials which are found near to the site and have low transport costs.

These strategies will not always be consistent with strategies for saving energy consumption in the use of a building, and in such cases it is necessary to examine the total energy consumption over a building's lifetime to determine which is the optimum energy saving strategy.

There will in some cases be a convergence between least− energy and least−cost designs, but the least−energy design may be in other cases not the least cost solution. Moreover, building codes and regulations may, in some cases, unnecessarily prohibit the use of materials such as stabilized soil, which can offer substantial energy and cost savings. The designer may also be unable to find information to assist in the selection of appropriate materials in a particular locality − the energy consumption figures given in table 2.1 are only indicative. Thus governments and policy−makers have a role in:

(a) Supporting research to provide building designers with detailed information on the energy costs of the entire range of available materials, and typical lifetime energy costs, to assist in materials selection for least energy;

(b) Examining building regulations, standard specifications, and codes of practice to permit the use of low− energy materials, particularly new or unfamiliar ones; utilizing them in building projects using public funds;

(c) Sponsoring research into the properties and performance of low−energy materials to enable designers to specify them for an increasing range of applications;

(d) Examining urban plans to find ways to create incentives to limit building heights so that low−energy materials can be used.

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